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U.S. Department
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**National Highway
Traffic Safety
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DOT HS 807 373

November 1988

Final Report

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Side Impact Sub-System Test Development: MVMA Thoracic Impactor Test Procedure and Evaluation

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Cotolog No.
DOT HS 807 373		

4. Title and Subtitle	5. Report Date
Side Impact Sub-System Test Development; MVMA Thoracic Impactor Test Procedure and Evaluation	November 1988
	6. Performing Orgonization Code: NRD-22
7. Author(s): Donald T. Willke and Michael W. Monk	8. Performing Orgonization Report No.: VRTC-86-0025
9. Performing Orgonization Name and Address: National Highway Traffic Safety Admin. Vehicle Research and Test Center P.O. Box 37 East Liberty, Ohio 43319	10. Work Unit No. (TRAIS)
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address: National Highway Traffic Safety Administration 400 7th Street, S.W. Washington, D.C. 20590	13. Type of Report and Period Covered: Final Report 11/85 - 4/88
	14. Sponsoring Agency Code

15. Supplementory Notes

MAY

16. Abstract

In the last several years, much attention has been devoted to the subject of side impact safety in passenger cars. An earlier study performed by the VRTC investigated the feasibility of performing sub-system, or component, level tests to assess thoracic injury potential in cars. During fiscal year 1985, the MVMA sponsored the development of a thoracic sub-system test device and associated procedures. This device was borrowed and installed at the VRTC.

This report contains the findings from a study done to evaluate the MVMA impactor and its associated procedures. This required the development of additional test procedures and parameters by the VRTC. The impactor/procedures were evaluated on their function as a hardware/software/data acquisition system, as well as on their ability to produce responses that could be used for thoracic injury assessment.

Three series of tests were performed using the impactor. First, its capability to distinguish between padded and unpadded door conditions was examined. Next, its ability to distinguish among various cars and between good and poor door/side structure designs was explored. Also, the results of one of the series of sub-system tests were compared to those from corresponding side impact crash tests. Finally, general usage of the device allowed for evaluation on various mechanical and software aspects of the impactor and its operating systems.

17. Key Words	18. Distribution Stotement
	Document is available to the public from the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72)

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Department of Transportation
National Highway Traffic Safety Administration

TECHNICAL SUMMARY

Report Title	
Side Impact Sub-System Test Development: MVMA Thoracic Impactor Test Procedure and Evaluation	November 1988

Report Author(s)

Donald T. Willke and Michael W. Monk

Over the last several years, much attention has been devoted to the problem of occupant safety in side impacts. Deriving a test and associated procedures for assessing the thoracic injury potential of cars in these types of collisions is an important step in solving this problem. A couple of years ago, the Vehicle Research and Test Center (VRTC) investigated the feasibility of performing sub-system, or component, level tests for this purpose. It was found that component test results indicated the same benefit from added padding to the inner door as crash tests, but were different from full-scale crash test results in discrimination among production vehicles.

During fiscal year 1985, the Motor Vehicle Manufacturer's Association (MVMA) sponsored the development of a thoracic sub-system test device and associated procedures. This device was subsequently borrowed and installed at the VRTC. Tests were performed which allowed for evaluation of the device and its associated procedures on several aspects. These included evaluating it on its function as a hardware/software/data acquisition system, as well as on its ability to produce responses that could be used in thoracic injury assessment. This required the development of additional test procedures and parameters by the VRTC.

Three series of tests were conducted on nine vehicle models that had previously been side impact crash tested. The first used the full body of each vehicle tested. These tests included fixturing the cars to the floor, performing an exterior pre-crush on each door/side structure, and impacting the interior of all the doors at the same pre-determined speed (18 mph - 29 km/h). For one of the vehicles, a second test was run, on a new door, which had the inner trim panel replaced by 3" (76.2 mm) of ArCel padding. There were three objectives from this series of tests. The first was to determine the ability of the impactor to distinguish between padded and unpadded doors. The second was to determine the ability of the device to differentiate production vehicles when tested at the same speed. Finally, exterior crush data was to be obtained for each vehicle.

The second series of tests was identical to the first except that adjusted impact speeds were used. These were determined separately for each car, based on the side structural strength of the particular vehicle, as measured in the pre-crushes performed during the first series of tests. There were two objectives for this second series of tests. The first was to allow a comparison between the results of the sub-system tests and those of the corresponding side impact crash tests. The second was to examine the ability of the sub-system approach to distinguish between good and poor door/side structure designs.

The last series of tests essentially followed the sub-system procedure suggested by the MVMA. This included mounting the doors in a rigid frame, performing a pre-crush, and impacting them at the same speed as the first series of full-body tests (18 mph - 29 km/h). This allowed for a comparison of the the fixtured door and full-body sub-system test approaches.

SIDE IMPACT SUB-SYSTEM TEST DEVELOPMENT
MVMA Thoracic Impactor Test Procedure and Evaluation

1.0 INTRODUCTION

The topic of testing to assess thoracic injury in side impacts has been of interest the last several years. An earlier study performed at the Vehicle Research and Test Center (VRTC) investigated the feasibility of performing sub-system, or component, level tests for this purpose (1). Upon comparison, it was found that the component test results indicated the same benefit from added padding to the inner door as crash tests, but were different from full-scale crash test results in discrimination among production vehicles.

During fiscal year 1985, the Motor Vehicle Manufacturer's Association (MVMA) sponsored the development of a thoracic sub-system test device and its associated test procedures. For the study of this project, this device was borrowed and installed at the VRTC. An evaluation of the device and test procedures has subsequently been completed.

This report reviews the test procedure developed at the VRTC for this program. This includes outlining the test objectives, defining test parameters to meet these objectives, and presenting the matrix of tests done. This report also presents the results of these tests and offers an evaluation on several aspects. These include evaluating the spring/damper system, the general hardware systems, and the software and data acquisition systems. Also included is a comparison of the results from tests performed using different test methodologies.

2.0 OBJECTIVES

The objective of this project was to evaluate the MVMA Thoracic Impactor and its associated procedures. This required the development of additional test procedures and parameters by the VRTC. It included an evaluation of the impactor on its function as a hardware/software/

data acquisition system, as well as on its ability to produce responses that could be used in thoracic injury assessment.

3.0 TEST PROCEDURE DEVELOPMENT

3.1 Test Objectives

In order to develop a test procedure and a matrix of tests, it was necessary to establish what the goals of the testing were. First, a test device and procedure should be capable of distinguishing between padded and unpadded door conditions. In addition, they should be able to differentiate among various cars and between good and poor door/side structure designs. A test matrix was developed to determine how well the MVMA device and procedures could accomplish these functions.

Another test objective was to compare the results of the sub-system tests with those of full-scale crash tests. This involved defining sub-system test parameters to simulate the crash environment as nearly as possible. This objective also made it necessary to select vehicles for testing which had previously been crash tested.

The suggested MVMA sub-system test procedure called for mounting the door in a rigid frame. Previous sub-system test programs done at VRTC utilized the full body of the vehicle, thereby testing not only the door but the surrounding side structure. A comparison of these methods was of interest. Therefore tests were planned to make this comparison.

Finally, it was felt that door-to-occupant contact velocities in crash tests may be related to some door/side structure property, such as stiffness. If this is true, then the impact velocities used for the sub-system tests should be dependent upon this property. Therefore, force versus deflection data from exterior static crush tests were collected for all doors tested, whether mounted in the vehicle body or in the frame.

3.2 Testing

To achieve the objectives outlined in the previous section, it was judged that three series of tests would be done. Test Series Number 1 utilized the full body of each vehicle tested. These tests included fixturing the cars to the floor, performing an exterior pre-crush on each door/side structure, and impacting the interior of all of the doors at the same pre-determined speed.

It was originally intended that two impact tests be performed on each door - one with padding on the door and one with the door in its baseline configuration. The first several tests were done this way; however, the results indicated that too much damage from the unpadded test occurred to permit a valid second, padded, test to be conducted on the same door. Therefore, for one vehicle, the door was replaced following the unpadded test, and a padded test was conducted. The remainder of the padded tests were not performed. From these tests, the ability of the device to distinguish between padded and unpadded doors, and to distinguish between different vehicles when tested at the same speed was determined. In addition, exterior crush force versus deflection data were collected for each vehicle. These were used in developing a velocity adjustment procedure based upon the side structural strength of a vehicle.

Test Series Number 2, similar to the first series, also used the full body of the vehicles. The impact velocity was determined separately for each car, using the velocity adjustment procedure developed from the exterior crush data obtained in the first series of tests. From these tests, the ability of the sub-system approach to distinguish between good and poor door/side structure designs was determined. Also, a comparison of these test results to those of the corresponding crash tests was made.

Finally, a third series of tests was done which esentially followed the sub-system test procedure suggested by the MVMA. This included mounting the doors in a rigid frame, performing a pre-crush on

each, and impacting them at the same pre-determined velocity as series 1. With these tests, a comparison of the door-in-frame and the full-body sub-system approaches was made.

As mentioned in Section 3.1, the vehicles selected for testing were those for which the Agency has crash test data. Several vehicle models had been tested, both by the NHTSA and the MVMA, under the same conditions. These conditions included using the NHTSA moving deformable barrier (MDB), equipped with an aluminum honeycomb face and crabbed to 26°, to impact the stationary vehicle with a nominal speed of 33.5 mph (53.9 km/h). This simulated a 90° collision with the striking vehicle moving 30 mph (48.3 km/h) and the struck vehicle having a speed of 15 mph (24.1 km/h). From these, the cars selected for sub-system testing were as follows:

4-door Chevrolet Celebrity
4-door Chevrolet Citation
2-door Dodge 400
2-door Ford Granada
4-door Plymouth Horizon
4-door Ford LTD
4-door structurally modified Ford LTD
2-door Volkswagen Rabbit
2-door Chevrolet Spectrum

Appendix A contains a summary of the testing done in these three series. This includes a statement of the objectives for each series as well as a statement of the various test parameters for these tests. The derivation of the test parameters are detailed in the following sections.

3.3 Impact and Pre-Crush Location

For each vehicle in each series of tests, it was necessary to determine certain test parameters. These include the impact location on the interior of the door, the location of the exterior pre-crush, and

the extent of this pre-crush. The impact velocities used were also determined. This included determining the velocity for the first and third series of tests, as well as developing a velocity adjustment procedure for determining the individual velocities for the second test series.

Since the full-body tests were to be compared to the crash tests, it was decided that the impact location on the inner door should be the same for these tests as that impacted by the SID in the corresponding crash test. To determine this location, the crash test film and pre-test photographs were closely examined for each case. The vertical line containing the center of the SID ribcage was located from each crash test. The impact for the corresponding sub-system test was centered on this line (see Table 3.1) and located such that the impactor face hit just below the window opening of the door.

Table 3.1
Horizontal Impact/Pre-Crush Locations
Full-Body Test

Vehicle	Impact Location *	Pre-Crush Location *
Celebrity	7"	9.5"
Citation	6"	8.5"
Dodge 400	21"	23.6"
Granada	18.5"	21"
Horizon	7.5"	10"
LTD	5.5"	8"
Rabbit	11.5"	14"
Spectrum	10.8"	13.2"

* distance forward of the lower rear corner of the window opening

It was also necessary to specify the location of the pre-crush for each car. The first series of full-body tests originally were to include both padded and unpadded tests on the same door. It was judged that the face of the impactor (8" diameter, 203 mm) should always be contained on the flat portion of the crusher face, which was about 13" (330 mm) wide. By centering the pre-crush 2 1/2" (54 mm) forward of the selected impact points listed in Table 3.1, the impactor face was still

contained on the flat portion of the crusher face. The impact locations for the padded tests were also to be contained on the flat portion of the crusher face, but located as far away as possible from the unpadded impact test locations. This meant that the impact location for the padded tests was to be 5" (127 mm) forward of that for the unpadded tests. Therefore, the longitudinal position for the pre-crush for each car was selected such that the vertical centerline of the crusher face was located 2 1/2" (64 mm) forward of the impact locations listed in Table 3.1. As mentioned in the previous section, padded tests were not done on several of the cars. The pre-crush locations were not altered, though, in order to remain consistent throughout the entire series. The one padded test performed on the replaced door used the same pre-crush and impact locations as the corresponding unpadded test. In order to allow for comparisons, the pre-crush location used for each car in the first series of full-body tests was also used in the second series of full-body tests.

The vertical location of the crusher face was determined using the suggested MVMA procedure. The bottom edge of this face was positioned 15.7" (400 mm) above the ground surface reference plane for the vehicle being tested. Using the lower rear corner of the closed front door as a reference, this position was found from the standard MVMA specifications for each vehicle (see Table 3.2).

The longitudinal interior impact and exterior pre-crush locations for the door-in-frame tests were found differently than for the full-body tests. Since only one test was done per door (no padded tests were performed), it was decided to center the impactor on the vertical centerline of the crusher face. As in the suggested MVMA procedure, the crusher face was positioned such that its vertical centerline passed through the mid-seat H-point. In cases where the crusher face was within 3" (75 mm) of the door opening, the crusher face was moved to achieve this minimum clearance. The horizontal impact/pre-crush locations used for these tests are listed in Table 3.3. The vertical pre-crush and impact locations were determined in the same manner as for the full-body tests.

Table 3.2
Vertical Pre-Crush Locations Full-Body Tests

Vehicle	Vertical Pre-Crush Location *
Celebrity	4.5"
Citation	4.8"
Dodge 400	5.6"
Granada	4.5"
Horizon	5.2"
LTD	5.9"
Rabbit	5.7"
Spectrum	5.8"

* distance from bottom edge of crusher face above lower rear corner of closed front door

Table 3.3
Horizontal Impact Locations Door-in-Frame Tests

Vehicle	Impact Location *
Celebrity	8.5"
Citation	7.8"
Dodge 400	22.5"
Granada	22.5"
Horizon	11.3"
LTD	11.5"
Rabbit	15.5"
Spectrum	17.3"

* distance forward of the lower rear corner of the window

The extent of the pre-crush was determined from the MVMA proposed sub-system test procedure. An exterior crush of 9.1" (230 mm) was applied to all doors/side structures. Once extended, the crusher face was held in this extended position throughout the conduct of the dynamic test. Inner panel displacments were also monitored for all tests.

3.4 Impact Velocity

One of the potentially critical test parameters that was to be determined was impact velocity. In crash tests, the moving barrier velocity was the same for each test. The actual contact velocity between the door and the occupant may be a function of the moving barrier velocity and the integrity of the struck vehicle's side structure. A good design appears to reduce this contact velocity more than a poor design, thereby offering a greater degree of occupant protection.

In a sub-system test, however, the impact velocity must be determined prior to testing. If all vehicles are tested at the same speed, benefits from superior door design may not be evident. Ideally, then, the impact velocity in a sub-system test would vary from vehicle to vehicle, being representative of the actual contact velocity which would be seen in a crash test of the particular vehicle. Determining these contact velocities, though, is not trivial.

Nine vehicles, listed previously, that had been crash tested were selected for sub-system testing with the MVMA thoracic impactor. An attempt was made to determine the door-to-occupant contact velocity for each test. Averaging upper and lower locations, average rib and spinal velocity time histories were found from the accelerations measured in the crash tests. For each test, a time, t(0.2), was found as follows:

$$t(0.2) = \min(t_r, t_s)$$

where t_r = time when average rib velocity exceeds 0.2 mph, and

t_s = time when average spinal velocity exceeds 0.2 mph.

Door accelerometers were integrated to give door velocity time histories and a contact velocity was found at t(0.2) for each accelerometer location. In addition, a second potential impact velocity was found as the maximum velocity at or prior to t(0.2). These two velocities per door location, $v_{0.2}$ and v_{max}, were found from both unfiltered and filtered velocity curves (a 50 Hz low pass filter was used). These curves and values were examined on an individual basis to determine whether or not they should be used in further analysis. This was done since door accelerations obtained during crash tests are frequently not realistic.

In each test, there were three to five front door accelerometers. The $v_{0.2}$ and v_{max} values for each door location that were judged to be good were averaged to obtain average door velocities for each car. The vehicles were then ranked based on peak rib, peak spine, and calculated door velocities.

Examination of these results led to several observations. First, the door velocities derived from door accelerations, by any method, were found to be unreliable. There was a lot of subjective judgement required in determining which door accelerations to use. The vehicle rankings based on calculated door velocities were counter-intuitive and did not generally correspond with the response levels (TTI) measured in the crash tests. In addition, many of the door accelerations were anomalous and could not be used. For these reasons, the door accelerometer information was not used to determine individual contact speeds, but was only used to determine a general range and overall average for contact velocities.

An average impact velocity was needed for the first series of full-body tests and the door-in-frame test series. The filtered $v_{0.2}$ and the unfiltered $v_{0.2}$ contact velocities were combined, giving an average calculated contact velocity of 17.7 mph (28.5 km/h). Rounding to the nearest integer, it was decided to run all the tests of these two series at 18 mph (29 km/h).

For the second series of full-body tests, it was still necessary to derive an individual contact speed for each of the cars to be used in a correlation with exterior crush properties. Peak rib and spinal velocities from the crash tests appeared to be more reliable, were more consistent, and gave vehicle rankings which were more intuitively satisfying than the door velocities. Unfortunately, these velocities differ from the actual contact velocities by rebound velocities and variations in the velocity during the loading on the dummy that are not easily determined. The rebound velocities are probably not constant from one vehicle to the next, although assuming them to be so may lead to reasonable contact velocities.

Since there was no one method that would confidently give contact velocities from the crash tests, all the previously mentioned velocities were used as possible independent variables in the STEPWISE routine of the Statistical Analysis System (SAS). These are listed in Table 3.4 and were defined as follows:

RIBV - peak average rib velocity
SPINEV - peak average spinal velocity
DR02NV - unfiltered $v_{0.2}$ values
DR02FV - filtered $v_{0.2}$ values
DRMAXV - filtered v_{max} values

The dependent variables for these regressions were taken from the force versus deflection data obtained from the exterior pre-crush performed on each vehicle in the first full-body test series. These were the stiffness (average slope of the rising portion of the force versus deflection curve), peak force, and crush energy (area under the rising portion of the force versus deflection curve) from each car. These are listed in Table 3.5.

STEPWISE was run using the data described above (see Appendix B for printouts of results). One and two variable models were found, but since there were a relatively small number of data points, only one variable models were considered. In addition, the best two variable

Table 3.4
CRASH TEST VELOCITIES
SAS Independent Variables

Vehicle	RIBV	SPINEV	DRO2NV	DRO2FV	DRMAXV
Celebrity	22.4	25.7	19.5	18.2	21.4
Citation	24.7	27.1	18.3	17.4	20.7
Dodge 400	25.3	26.1	21.2	18.0	18.1
Granada	23.6	26.7	18.2	21.9	26.1
Horizon	24.6	27.1	15.8	14.1	18.4
bas LTD	22.5	26.0	16.2	15.1	19.3
mod LTD	19.5	21.6	15.0	14.3	20.9
Rabbit	25.5	27.2	24.0	17.5	18.6
Spectrum	24.8	29.6	15.2	18.4	20.6
average	23.7	26.3	18.2	17.2	20.5

note: all velocities in mph

Table 3.5
EXTERIOR CRUSH RESULTS
Full-Body Test Series No. 1 SAS Dependent Variables

Vehicle	Stiffness (lb/in)	Intercept (lb)	Peak Force (lb)	Crush Energy (ft·lb)
Celebrity	920	115	7580	3252
Citation	904	652	7744	3624
Dodge 400	777	684	6793	3228
Granada	947	55	7606	3245
Horizon	690	1490	6962	3516
bas LTD	774	325	6548	2911
mod LTD	1770	-936	13,382	5308
Rabbit	666	806	6119	2903
Spectrum	633	1062	5768	2956

model only showed a 6.5% increase in the coefficient of determination (r^2) over the best one variable model.

Table 3.6 lists the r^2 values for the one variable regressions done on each of the dependent variables. Not surprisingly, the door velocities produced no correlation with any of the crush properties. When stiffness (STIFF) and peak force (FORCE) were used, a good correlation did exist with both rib and spinal peak velocities. Although stiffness and peak force produced nearly the same coefficient of determination when correlated with peak spinal velocity, stiffness was chosen as being more representative of the entire exterior crush event than peak force. Thus, spinal velocities could be predicted from the stiffness of a vehicle's door/side structure by the following relationship:

$$SPINEV = 31.28 - 0.00549(STIFF)$$
$$r^2 = 0.81$$

where STIFF is in lb/in and SPINEV in mph.

Table 3.6
REGRESSION SUMMARY

r^2 values

Variable	RIBV	SPINEV	DRO2NV	DRO2FV	DRMAXV
STIFF	0.75	0.81	0.12	0.08	0.08
FORCE	0.71	0.81	0.14	0.13	0.05
ENERGY	0.55	0.68	0.18	0.20	0.01

Figure 3.1 shows the line predicted by this relationship along with the actual data points from the nine cars tested. Note that this regression was heavily influenced by the rightmost data point (modified LTD). Using this equation, a predicted spinal velocity was calculated

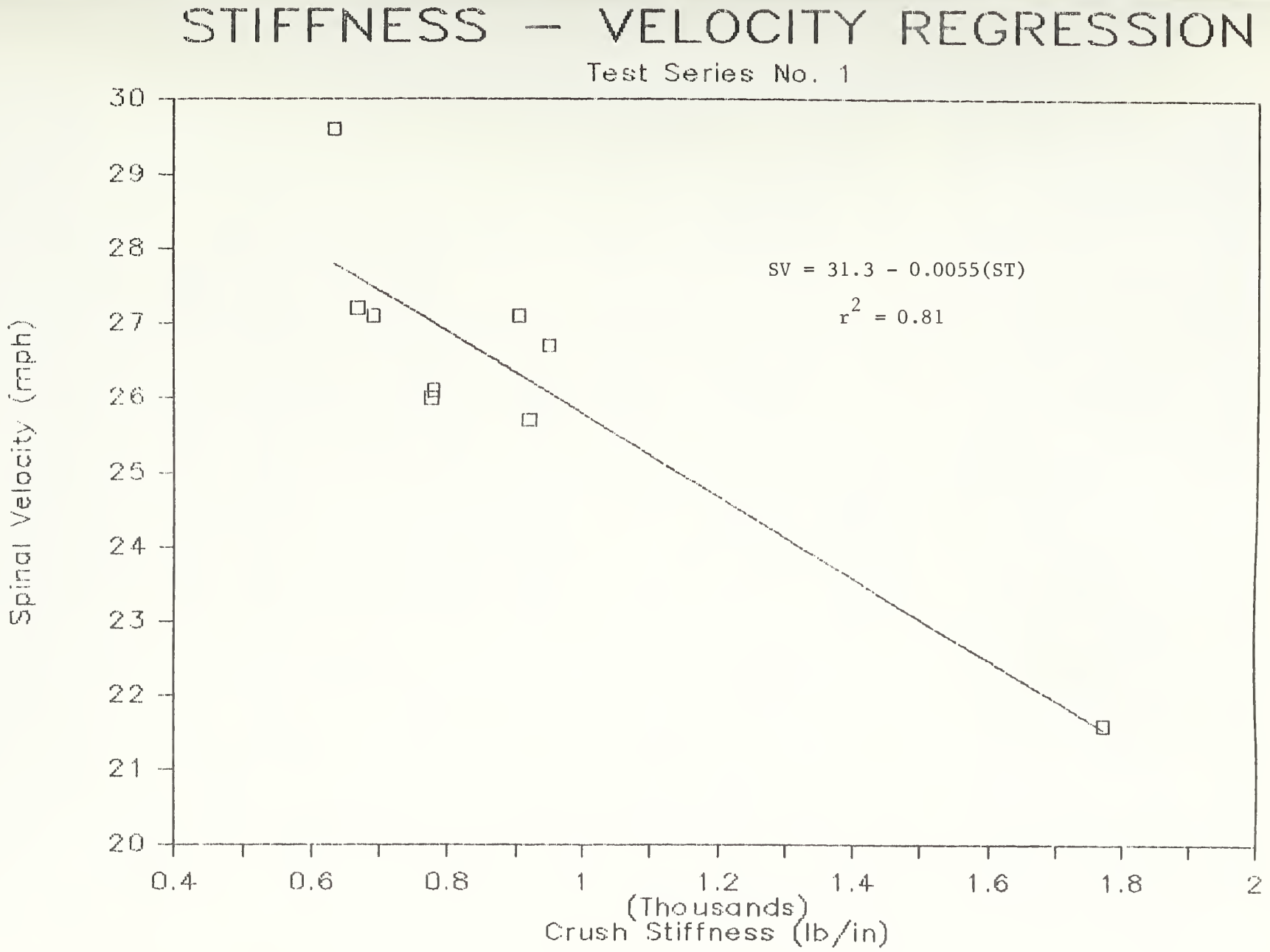


Figure 3.1. Side Crush Stiffness - Spinal Velocity Correlation

for each car (see Table 3.7). As mentioned previously, spinal velocity differs from the actual contact velocity by some rebound velocity. Based on the approximation that rebound velocity was a constant percentage of the spinal velocity, contact velocities were estimated by normalizing the predicted spinal velocities to the average contact velocity of 18 mph (29 km/h) derived previously. These predicted contact velocities, also listed in Table 3.7, were used as the impact speeds for the second series of full-body tests.

Table 3.7
ADJUSTED VELOCITIES
Regression Results

Vehicle	Stiffness (lb/in)	Actual Spinal Velocity (mph)	Predicted Spinal Velocity (mph)	Predicted Contact Velocity (mph)
Celebrity	920	25.7	26.2	17.9
Citation	904	27.1	26.3	18.0
Dodge 400	777	26.1	27.0	18.5
Granada	947	26.7	26.1	17.9
Horizon	690	27.1	27.5	18.8
bas LTD	774	26.0	27.0	18.5
mod LTD	1770	21.6	21.6	14.8
Rabbit	666	27.2	27.6	18.9
Spectrum	633	29.3	27.8	19.0
average	XXX	26.3	26.3	18.0

3.5 Padding

As indicated in section 3.1, the MVMA thoracic impactor was to be evaluated to determine its ability to distinguish between padded and unpadded door conditions. The padding selected for use was that used in

the MVMA MDB-to-Ford LTD crash tests (2). This was ArCel padding, which had a nominal density of 2 lb/in^3 (32 kg/m^3).

The results of the crash tests of Reference 2 indicated that this padding was too stiff, thereby not offering as much protection to the occupant as was possible. Softening the padding, to a point, would reduce the impact severity. Beyond that point, when the padding becomes too soft, impact severity increases. A limited attempt was then made to determine this "optimum" stiffness.

First, an 18 mph (29 km/h) test was done into a rigid surface, recording both small and large mass accelerations as well as the relative deflection between the two masses. A second test, also at 18 mph (29 km/h), was done into a 3" (76 mm) thick piece of 8" x 12" (203 x 305 mm) ArCel padding. Table 3.8 compares the peak accelerations and relative deflections from these tests. As can be seen, the padding produced a significant decrease in the small and large mass peak accelerations as well as in the relative deflection over the rigid impact (41%, 44%, and 9%, respectively).

Table 3.8
PADDING STIFFNESS RESULTS
18 mph

Impact Surface	Acceleration (g)		Relative Deflection (inches)
	small mass	large mass	
Rigid	171.4	83.6	2.97
Padding	101.3	47.1	2.70
Padding With Holes	66.4	45.3	2.67

A second piece of ArCel padding was also tested at 18 mph (29 km/h). It had the same exterior dimensions as the first, but had nine 7/8" (22 mm) holes drilled through it vertically (see Figures 3.2 and 3.3). Note that Figure 3.3 shows padding mounted on a car door, not on

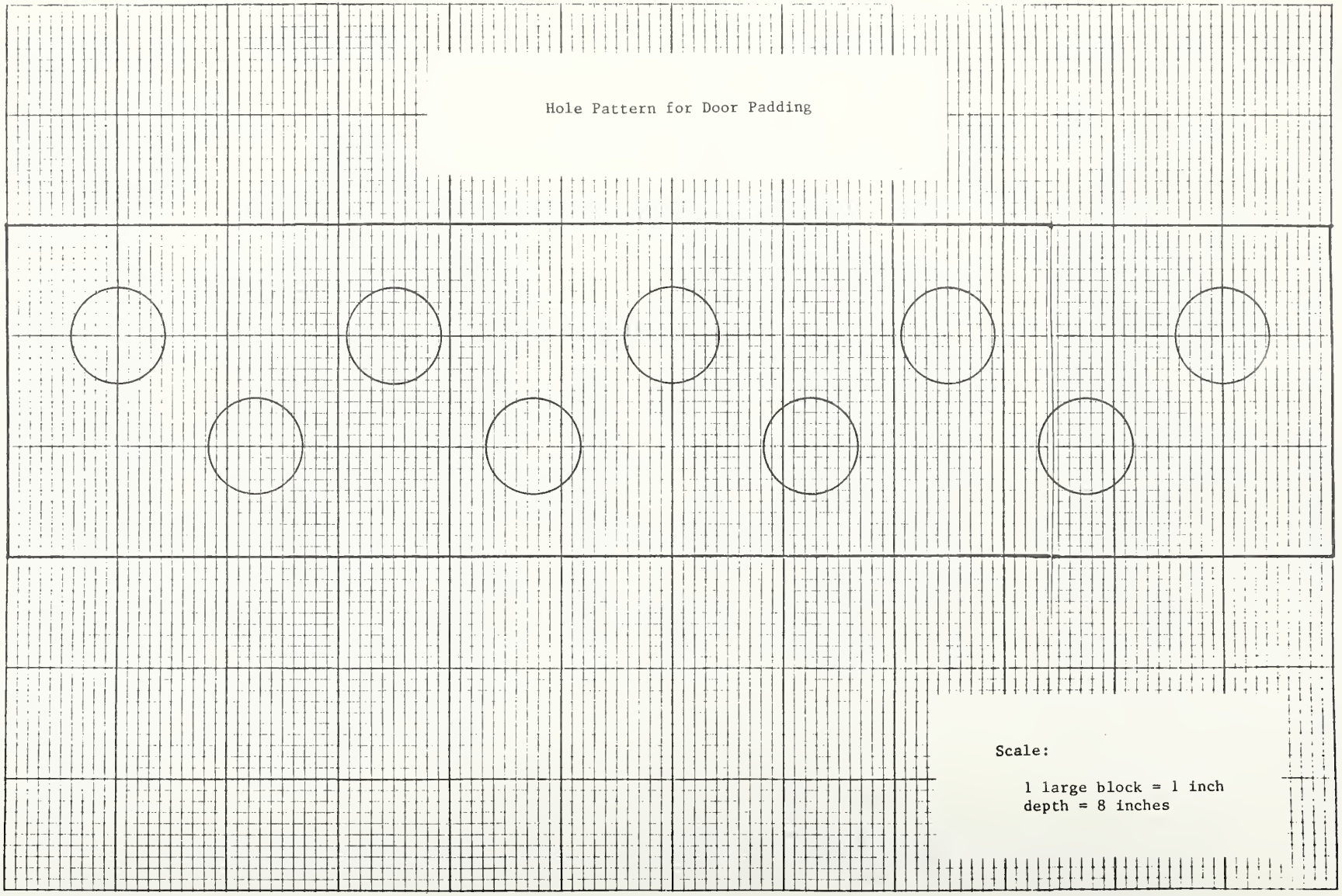


Figure 3.2. Hole Pattern for Softening Door Padding

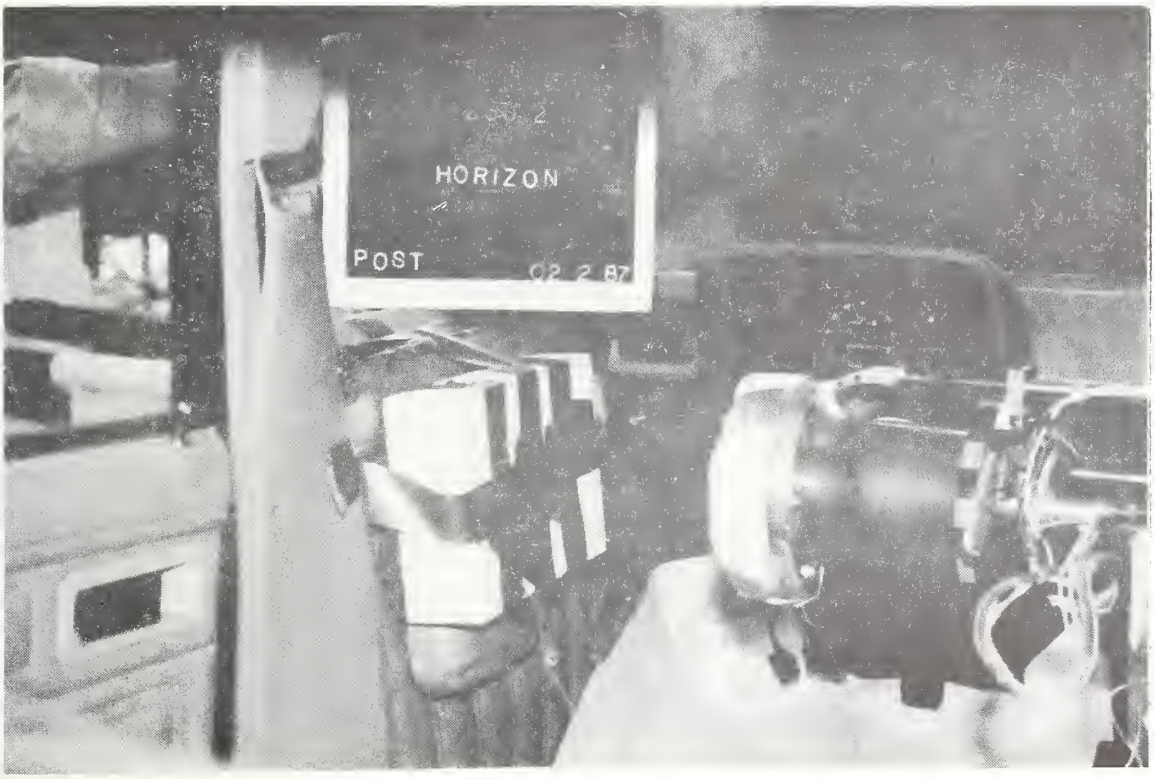


Figure 3.3. Padding on Crushed Door

the rigid surface. These holes were intended to reduce the effective stiffness of the padding. The results of this test are also listed in Table 3.8. The large mass peak acceleration and relative deflection remained essentially unchanged from the previous padding test, but the small mass response showed another sizable decrease (34%).

Because the small mass acceleration decreased, this reduced stiffness padding represented an improvement over the original padding. It was recognized that an even softer padding might be closer to the "optimum" stiffness when mounted to an actual door since the door acts as a spring in series with the padding. However, this was intended to be a limited investigation, so the reduced stiffness padding described above was selected for use in the padded full-body test.

3.6 Hardware

In order to perform the required tests, support hardware for the impactor was needed. This included a frame to support the impactor, a pre-crush device, a means to secure the car to the ground in the full-body tests, and a frame to mount the doors for the door-in-frame tests. This section describes the hardware used as well as the general test set-up.

Figure 3.4 gives an overview of the hardware. The vehicles were positioned between parallel I-beams which were bolted to the floor. Raised off of their suspension, the cars attached to cross-horses at both the front and rear bumper mount locations (see Figures 3.5 and 3.6). These cross-horses fastened to the I-beams. To further reduce body movement, chains were added in line with the direction of crush as shown in Figure 3.7. Early tests indicated that this method of securing the vehicles results in essentially no general body movement during the pre-crush phase of testing.

The pre-crushes were accomplished with the apparatus shown in Figure 3.8. Powered by a servo-controlled hydraulic pump, a 4" diameter piston pushed the crush plate into the side of the vehicle being tested.

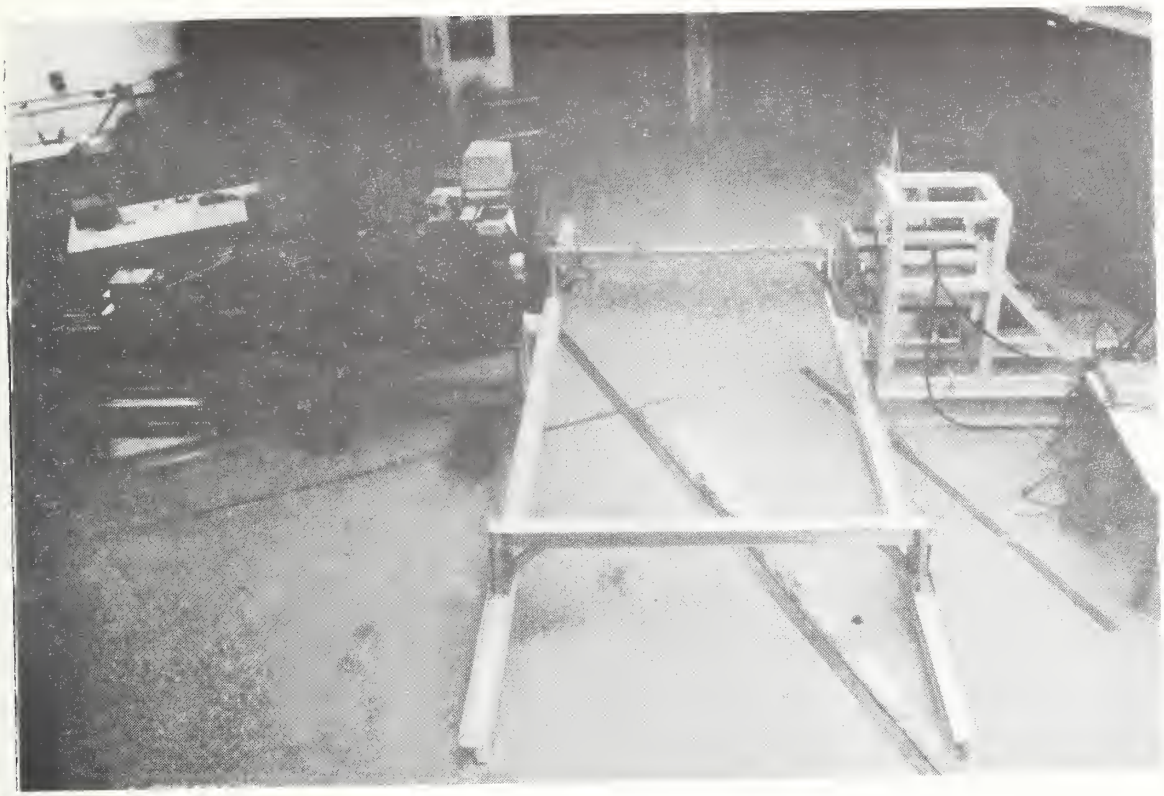


Figure 3.4. Overview of Test Hardware

Figure 3.5. Front Bumper Attachment

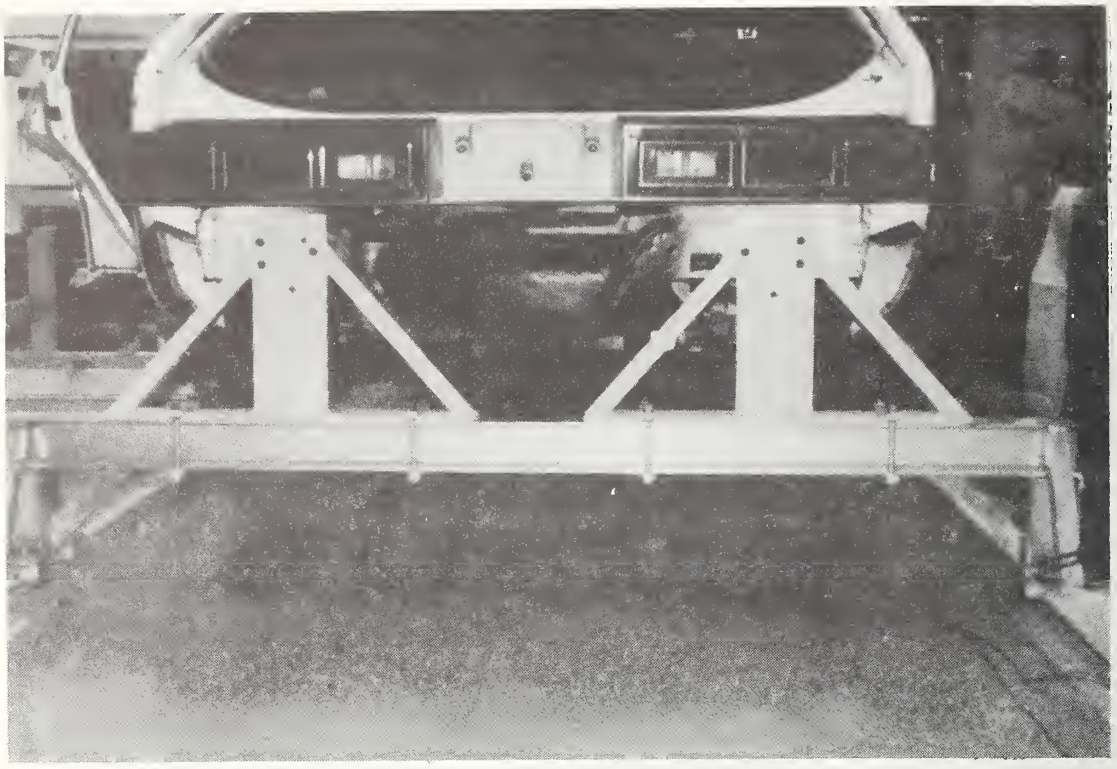


Figure 3.6. Rear Bumper Attachments

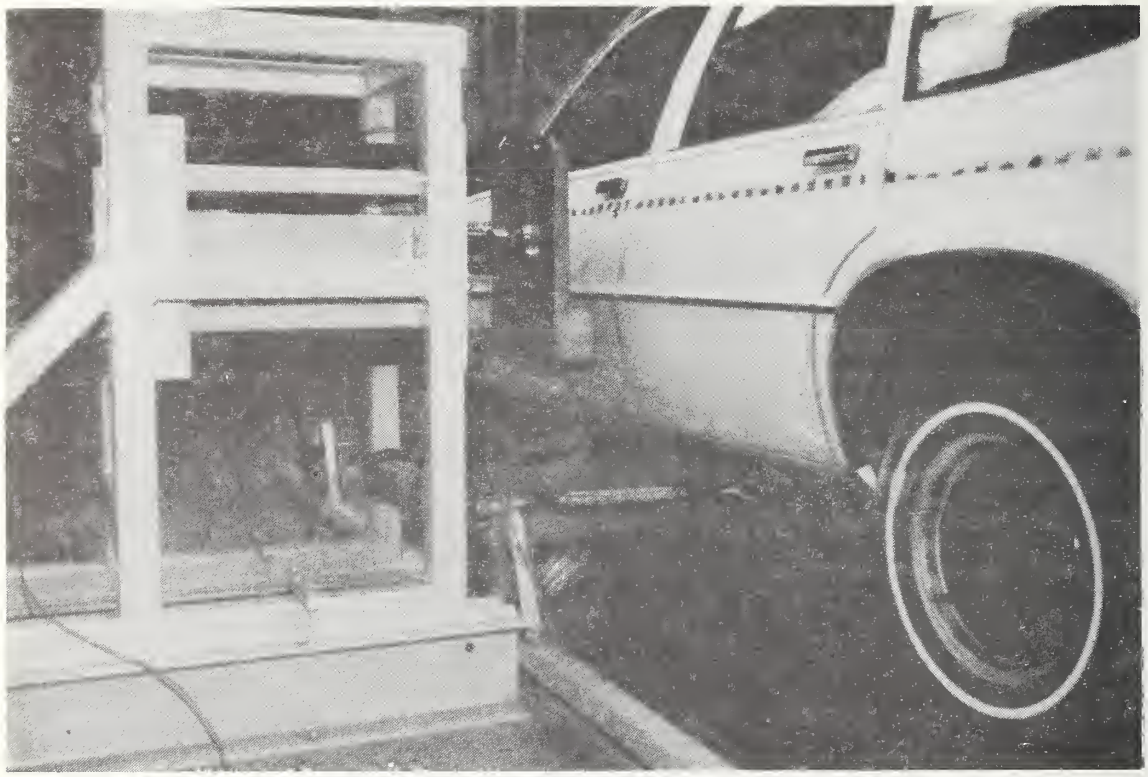


Figure 3.7. Chain Reinforcements

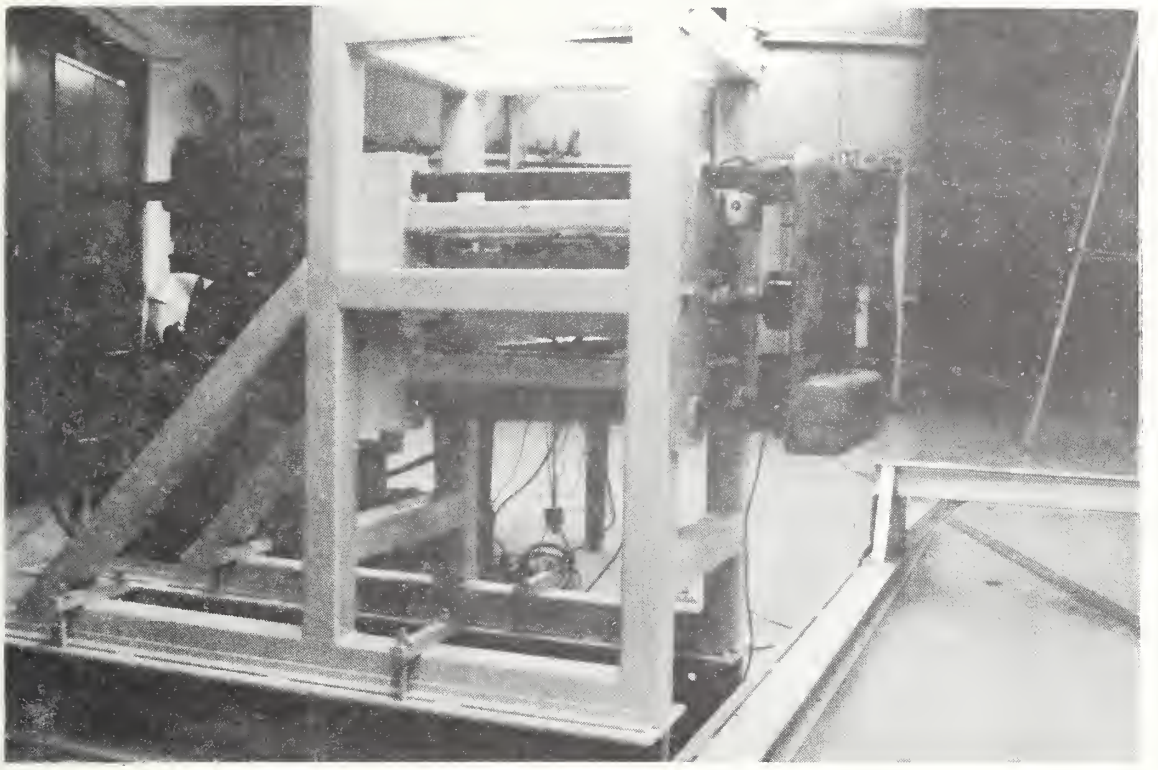


Figure 3.8. Pre-Crush Device

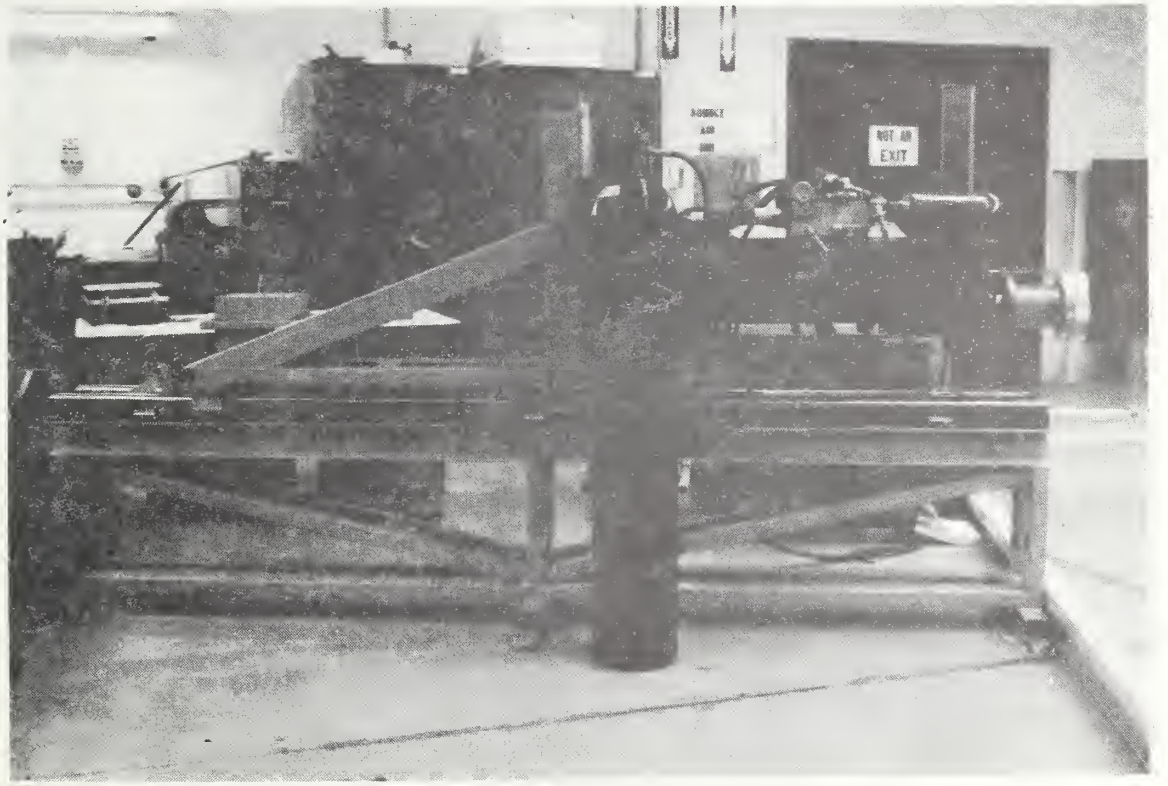


Figure 3.9. MVMA Impactor and Support

This was a cast aluminum plate identical to the one used in the sub-system tests performed for the MVMA (3). This device could be adjusted to achieve the desired vertical position for the crush plate. The entire pre-crush apparatus could also be adjusted laterally relative to the car (left to right in the photo).

A frame was built to support and position the impactor itself (see Figure 3.9). The frame allowed the impactor to reach into and across the width of the car being tested and to also be easily moved out of the way to allow vehicle installation. The impactor was mounted on a triangular frame and could be adjusted vertically on this component. The triangular frame was attached to a rectangular sub-frame by means of linear bearings which permitted movement of the impactor into and out of the vehicle being tested. The triangular frame and impactor were secured prior to performing a test. The rectangular sub-frame was also capable of limited adjustment in the longitudinal direction relative to the car (in and out of the page).

Finally, a frame was built for mounting the doors tested (see Figure 3.10 and 3.11). The doors mounted to two posts by their hinges and latches/striker pins. The periphery of the doors was also supported along the bottom and sides by means of bars mounted in a backup frame. These supports simulated the door opening of the vehicle, except that they were rigid.

4.0 HARDWARE AND SOFTWARE SYSTEMS EVALUATION

4.1 APPROACH

As indicated previously, the most crucial aspect of this program was to evaluate the ability of the impactor and its associated procedures to assess the thoracic injury potential of vehicles. This was accomplished by performing the three series of tests outlined in section 3.2 and summarized in Appendix A. Since the impactor was also to be evaluated on various other aspects, several additional sets of tests were performed.

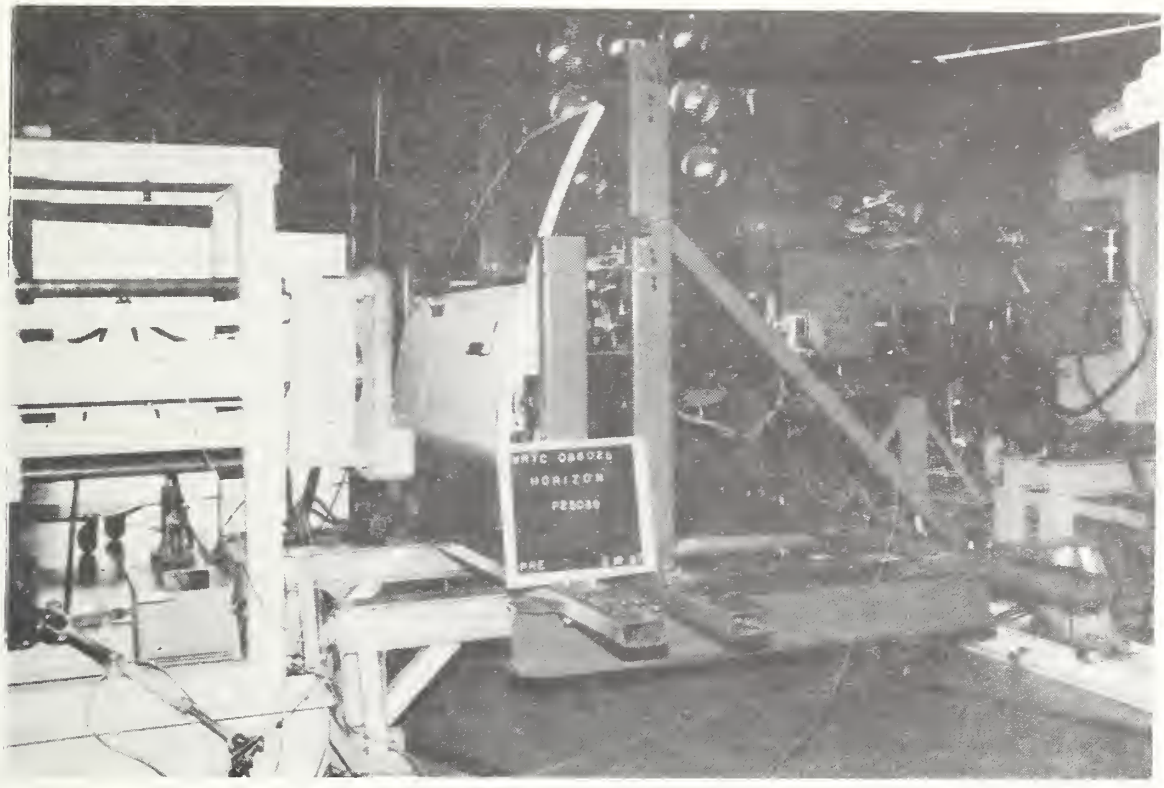


Figure 3.10. Door Frame -- Side View

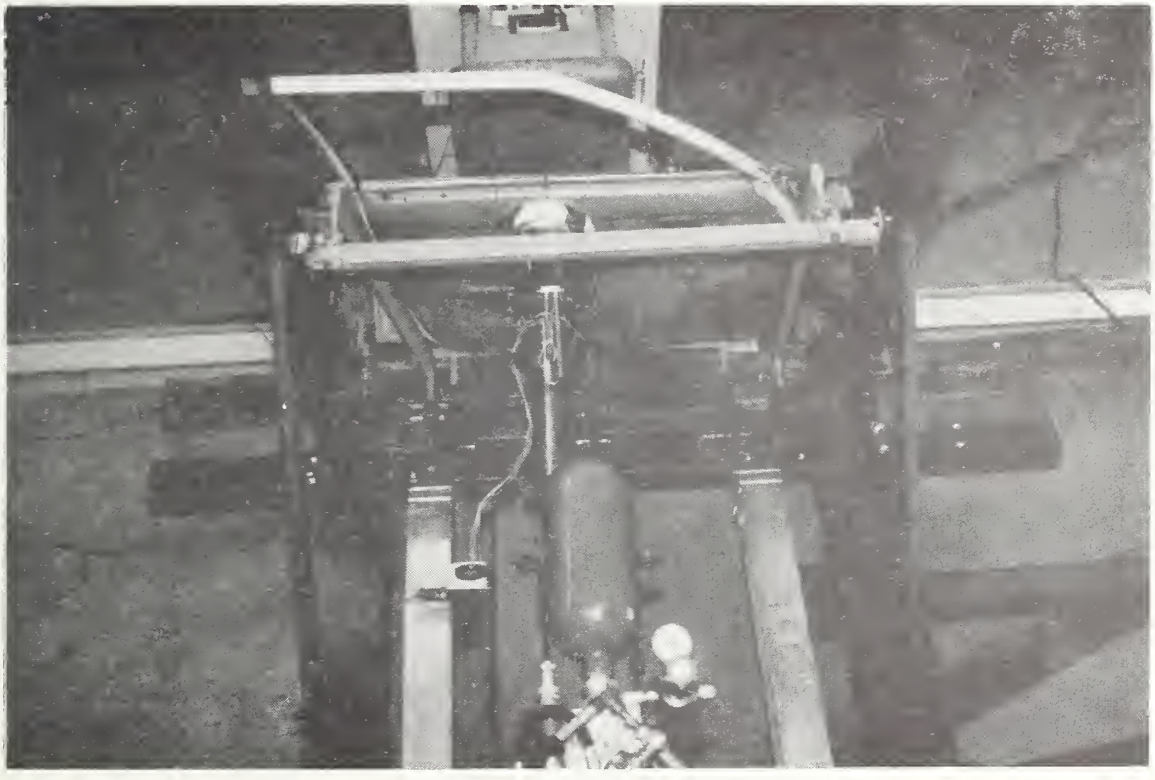


Figure 3.11. Door Frame -- Top View

The purpose of the first few sets was to examine the response characteristics of the impactor. Since the impactor was to meet the force/time and peak relative deflection corridors established from the one and two meter cadaver drop tests performed by Association Peugeot-Renault (APR) (4), and normalized by Krause (5), calibration tests at these two speeds (9.91 and 14.01 mph - 15.95 and 22.55 km/h, respectively) were performed. In addition, a series of tests at speeds ranging from 0 to about 20 mph (32 km/h) were performed to document the relative deflection between the small and large masses at the various velocities. Finally, a static crush of the impactor was done to obtain a force/deflection trace of the device's spring/damper system.

An alternate spring/damper system was then installed on the impactor. To investigate the response characteristics of this system, calibration, varying speed, and static crush tests were done. The results of these were compared to those from the original system.

Finally, through using the device, the general hardware systems were evaluated on such things as durability, ease of use, and susceptibility to problems. Likewise, the ease of use, susceptibility to problems, and compatability between the data acquisition and software systems were also noted.

4.2 Spring/Damper System

The MVMA Thoracic Impactor was a two mass system connected by a spring/damper element. A schematic view of the impactor is shown in Figure 4.1. The spring/damper element was actually composed of two parts, a cylindrical Urethane main "spring" between the two masses and a conical secondary "spring". Upon impact, the small mass moved toward the large mass, thereby compressing the Urethane spring. After about 1 inch (25 mm) of relative deflection, compression of the conical spring began. This continued for the rest of the stroke between the two masses, for a total of about 3.2 inches (81 mm). These springs were obviously a major factor in determining the dynamic response characteristics of the impactor.

MVMA THORACIC IMPACTOR

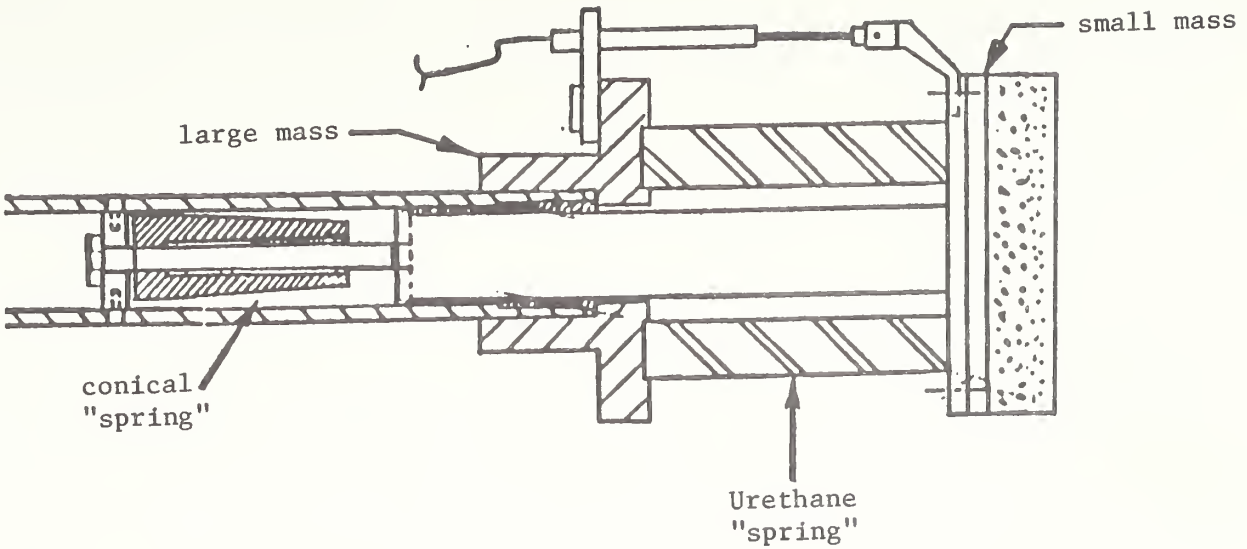


Figure 4.1

As mentioned in the previous section, several means were used to measure the response characteristics of the impactor. First, calibration impacts were performed into a rigid surface at both the 1 and 2 meter drop speeds (9.91 and 14.01 mph - 15.95 and 22.55 km/h, respectively). The force/time histories from these calibration tests, as compared to the APR corridors, are shown in Figures 4.2 and 4.3. At the lower speed, the resulting force curve followed the corridor fairly well during the loading portion, but reached a peak about 350 lbs (159 kg) above the upper limit of the corridor. At the 2 meter drop speed, the resulting force curve stayed within the corridor for essentially the entire event. These results were similar to those obtained by the MVMA from earlier testing.

The peak relative deflections measured for these tests were 1.40" and 2.43" (35.6 and 61.7 mm), respectively. The calibration ranges for these values were as follows:

1 meter - 1.06 to 1.30" (26.9 to 33.0 mm)

2 meter - 1.54 to 1.85" (39.1 to 47.0 mm)

As can be seen, the device did not meet the peak deflection criterion established.

Slow-rate crush tests were also done on the impactor spring elements to document their force/deflection characteristics. The Urethane spring is shown at progressive levels of relative displacement between the large and small masses in Figure 4.4. At a little over 1" (25 mm) of crush, the spring began to bulge and by 1 1/2" (38 mm) or so, it began to buckle. A progressive crush on the conical spring is shown in Figure 4.5. It failed by 'necking in' at about mid-length. The force versus deflection curve obtained from static crush of the combined springs is contained in Figure 4.6. Note that force rose linearly for about 1.4" (36 mm) of crush, at which point the resistance to crush from the Urethane spring dropped off due to bulging/buckling. Following this, the conical spring began to carry a larger portion of the load. As deflection continued, the conical spring buckled and shortly after, began to bottom out in the device, causing the resulting load to increase sharply.

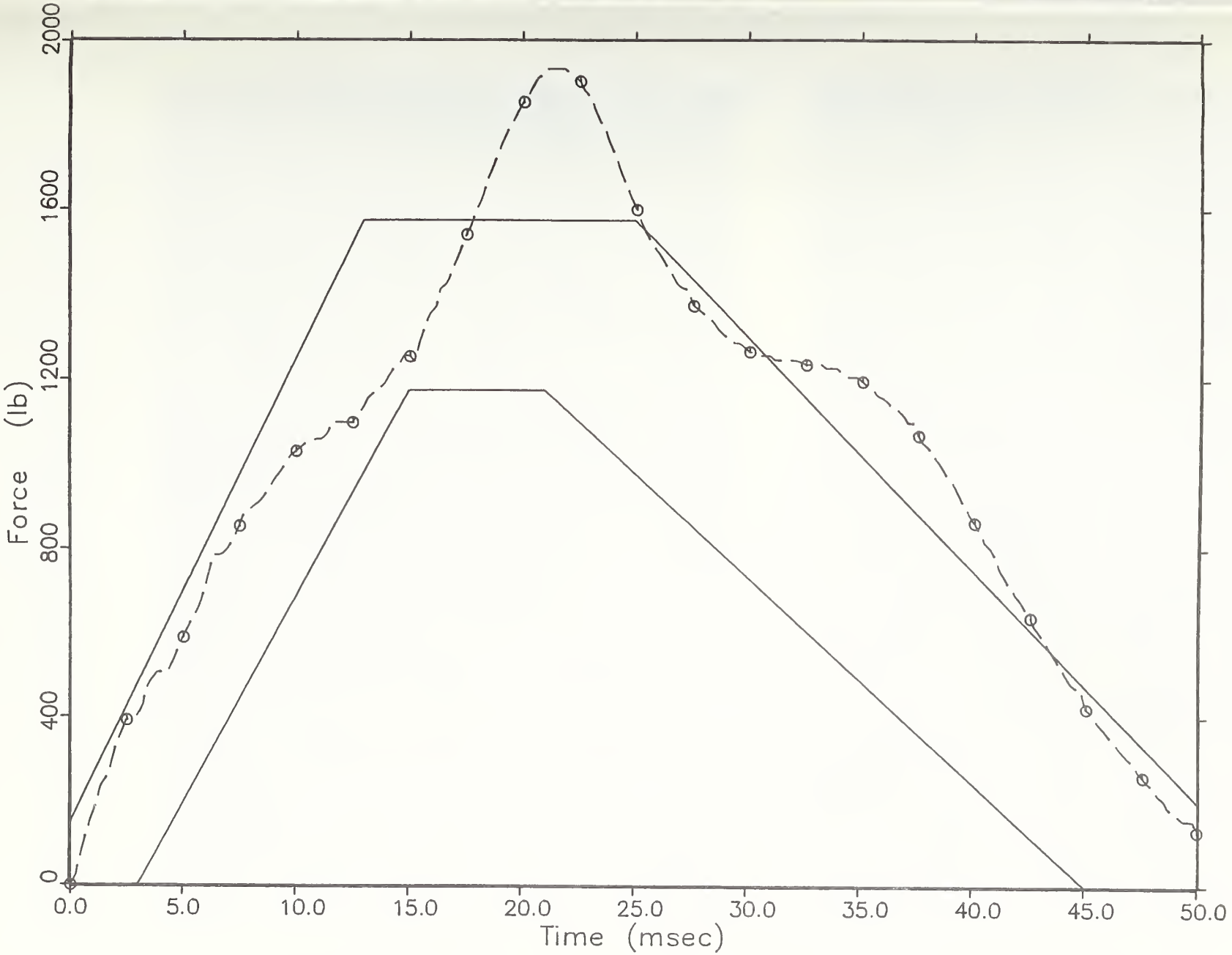

2000
1600
1200
800
400
0
Force (lb)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
Time (msec)
1 m CALIBRATION — URETHANE SPRING SYSTEM

Figure 4.2

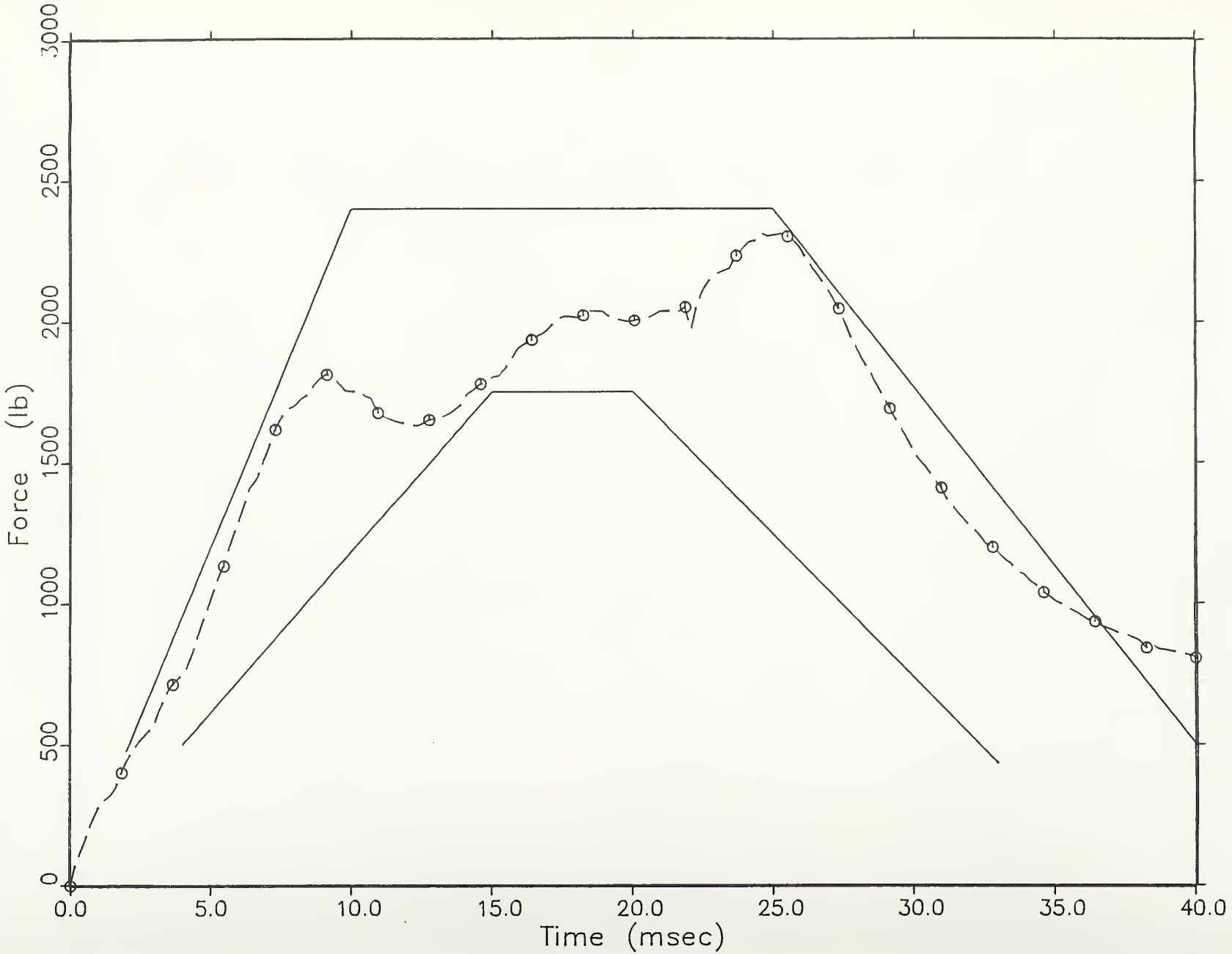
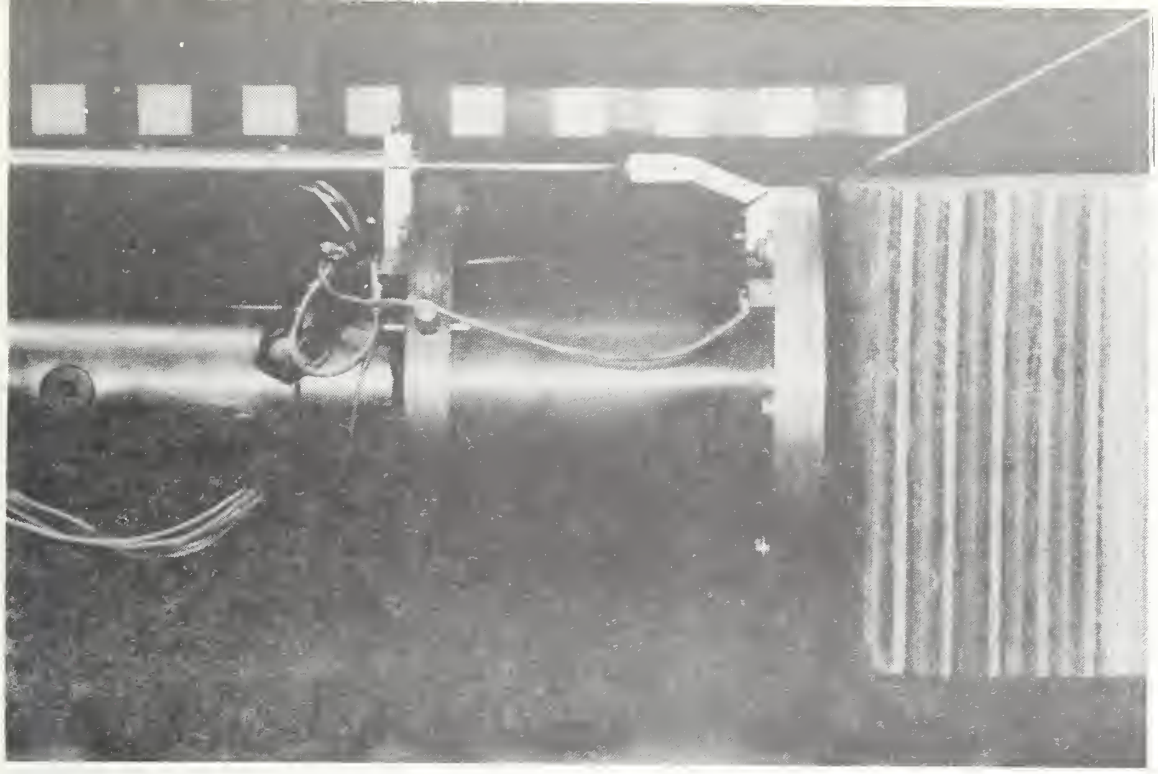
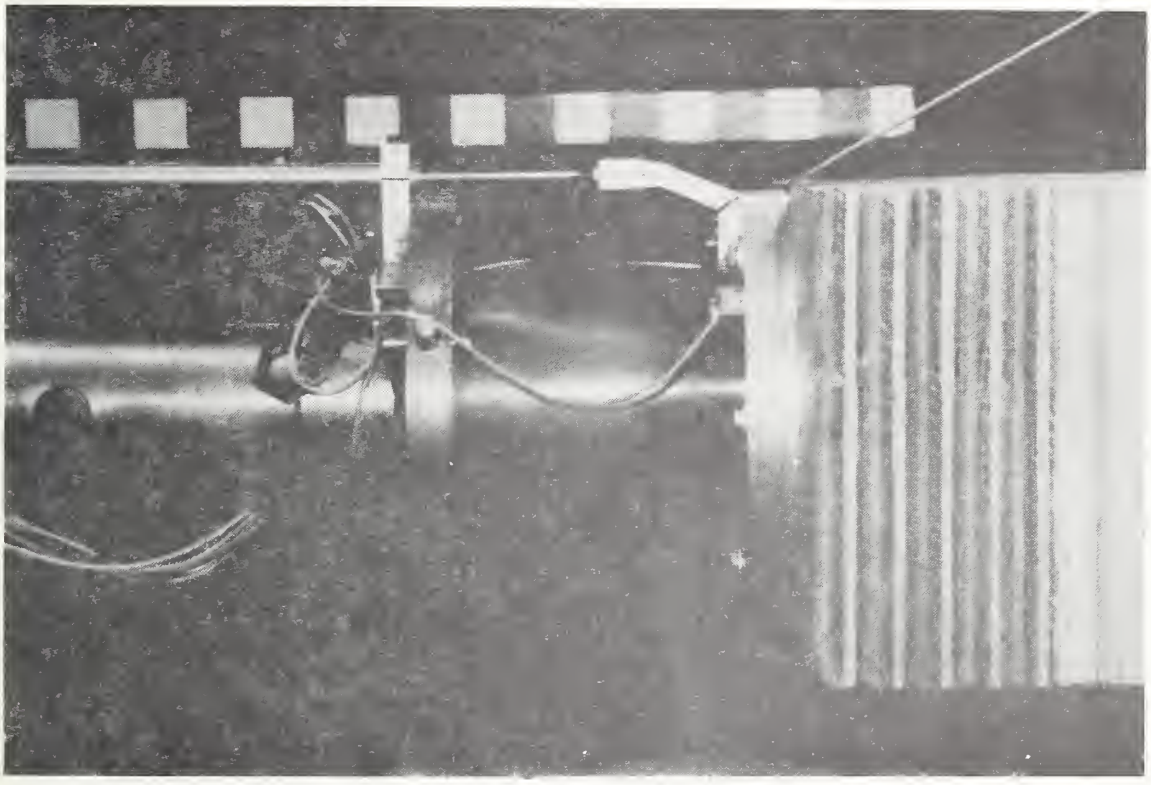

Force (lb)
0
500
1000
1500
2000
2500
3000
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
Time (msec)
2 m CALIBRATION — URETHANE SPRING SYSTEM

Figure 4.3

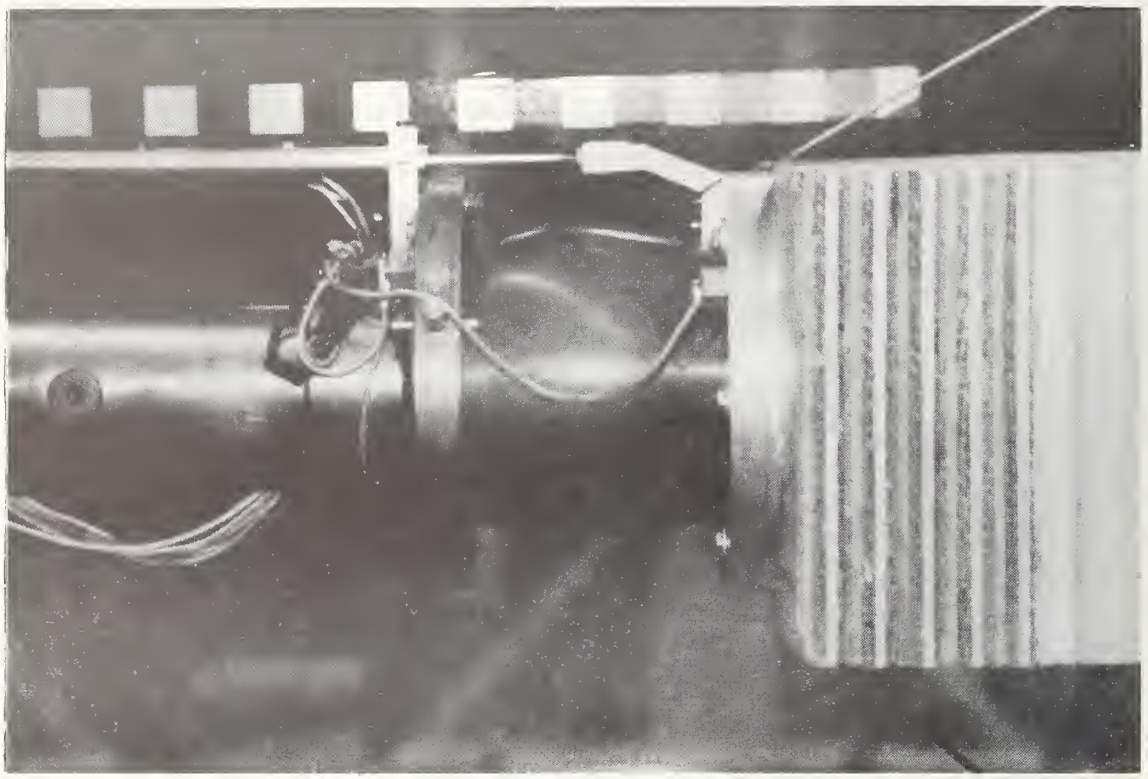


a. 0"

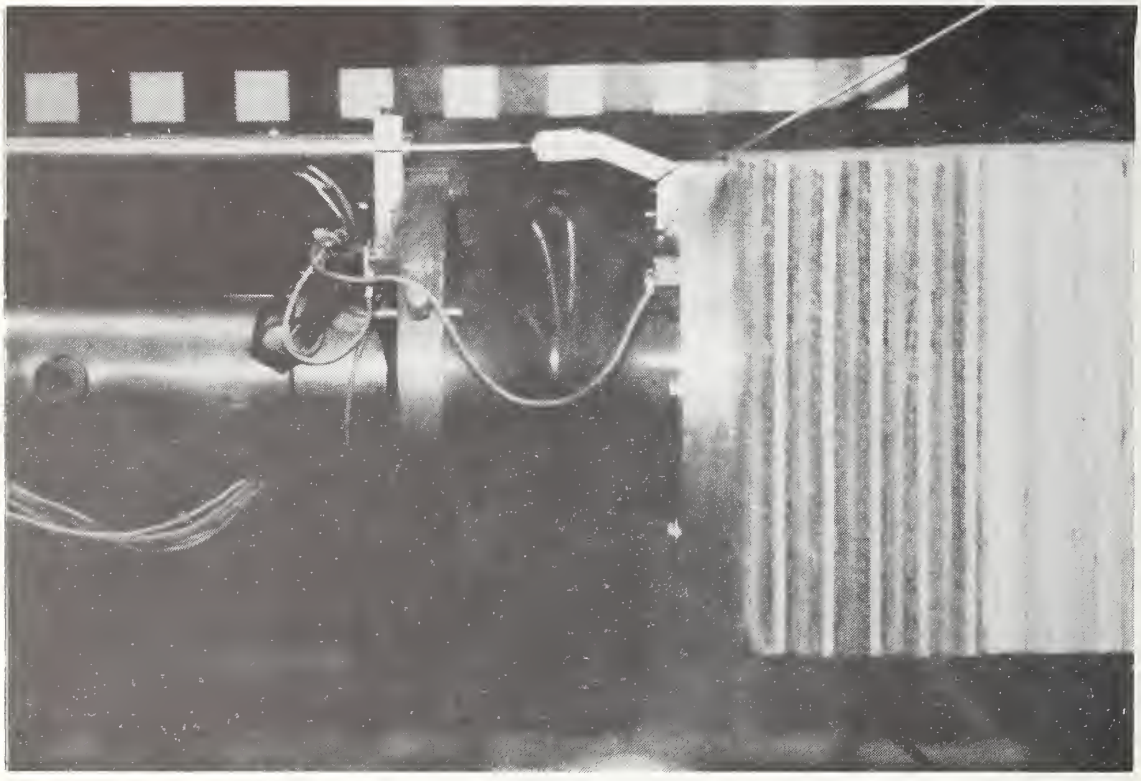


b. 3/4"

Figure 4.4 -- Urethene Main Spring Progressive Crush

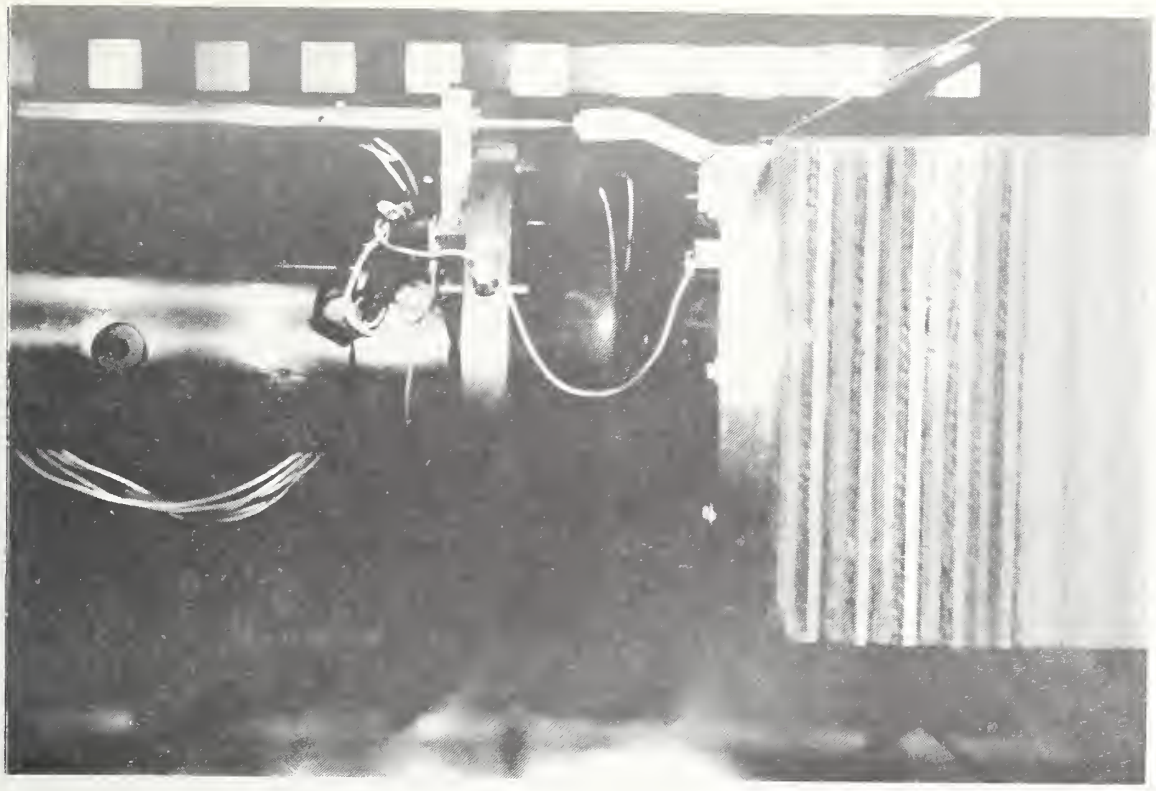


c. 1-1/4"

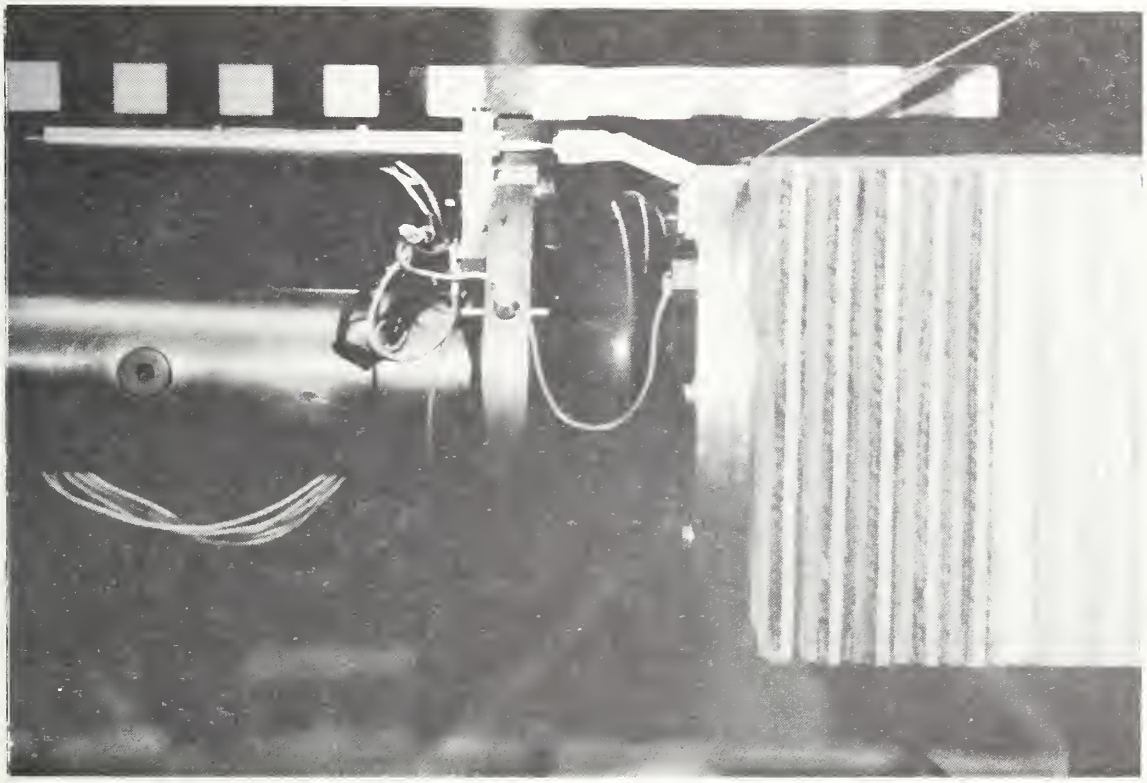


d. 1-3/4"

Figure 4.4 (Continued) -- Urethene Main Spring Progressive Crush

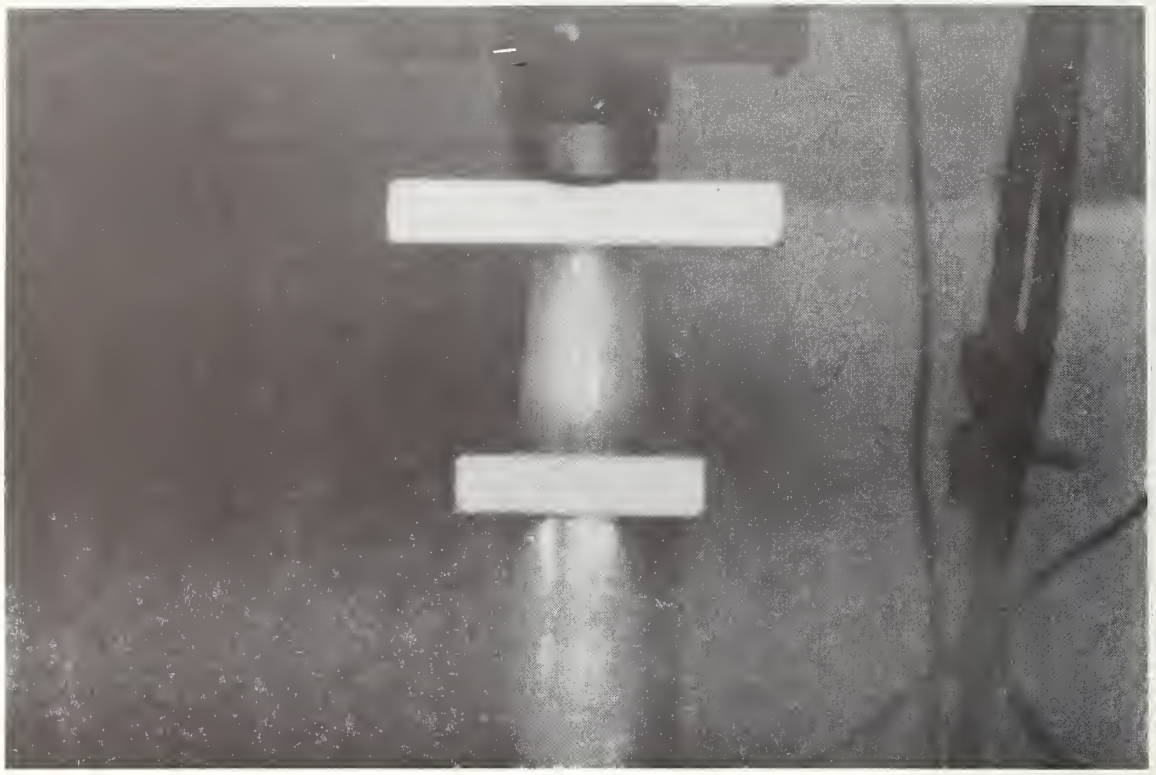


e. 2-1/4"

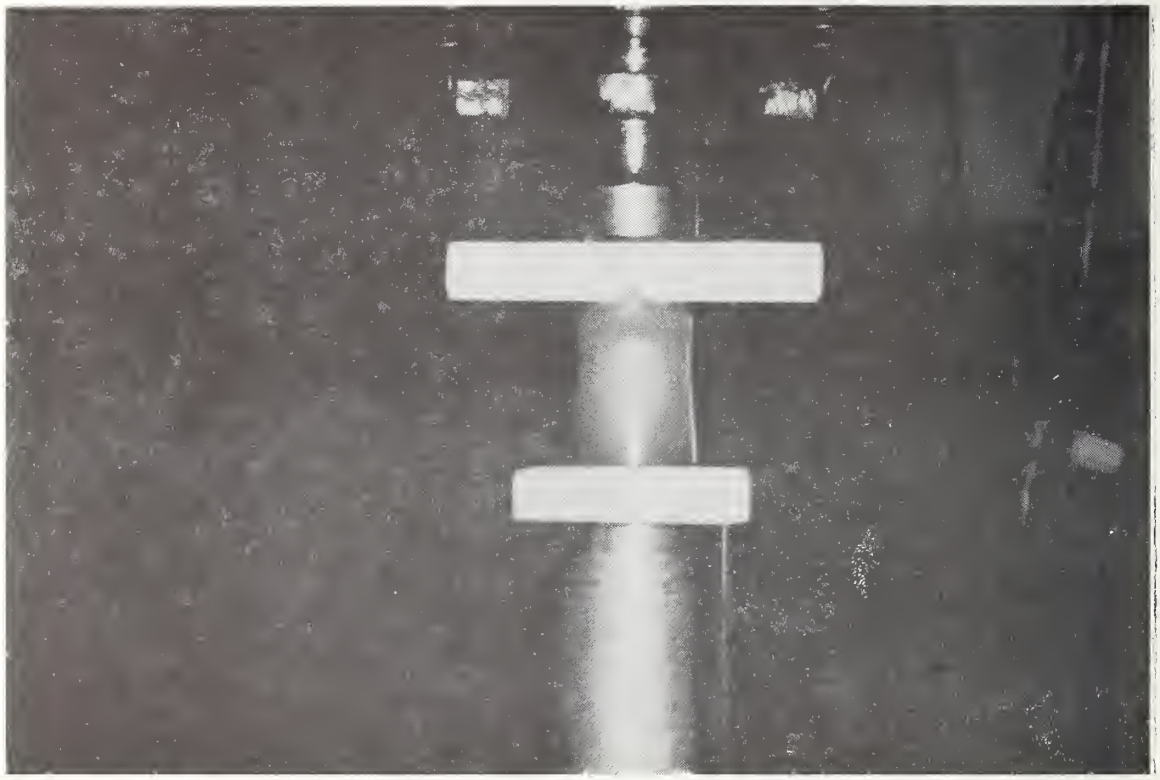


f. 3"

Figure 4.4 (Continued) -- Urethene Main Spring Progressive Crush

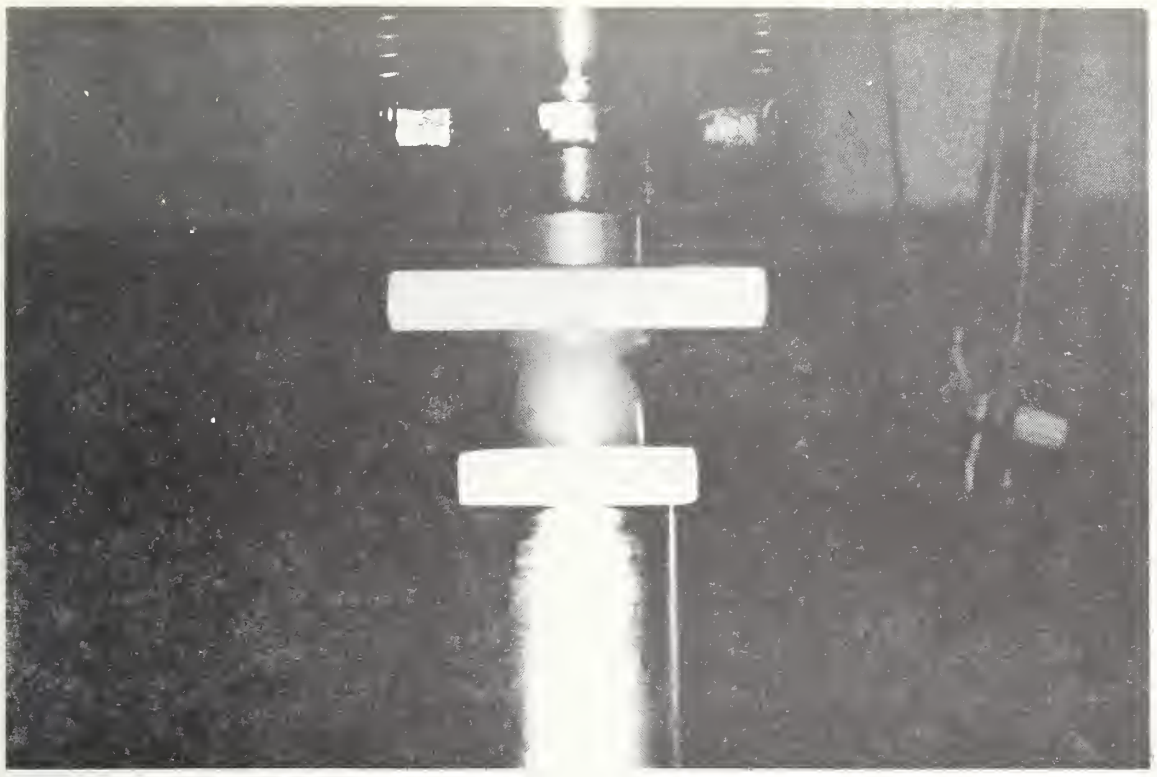


a.

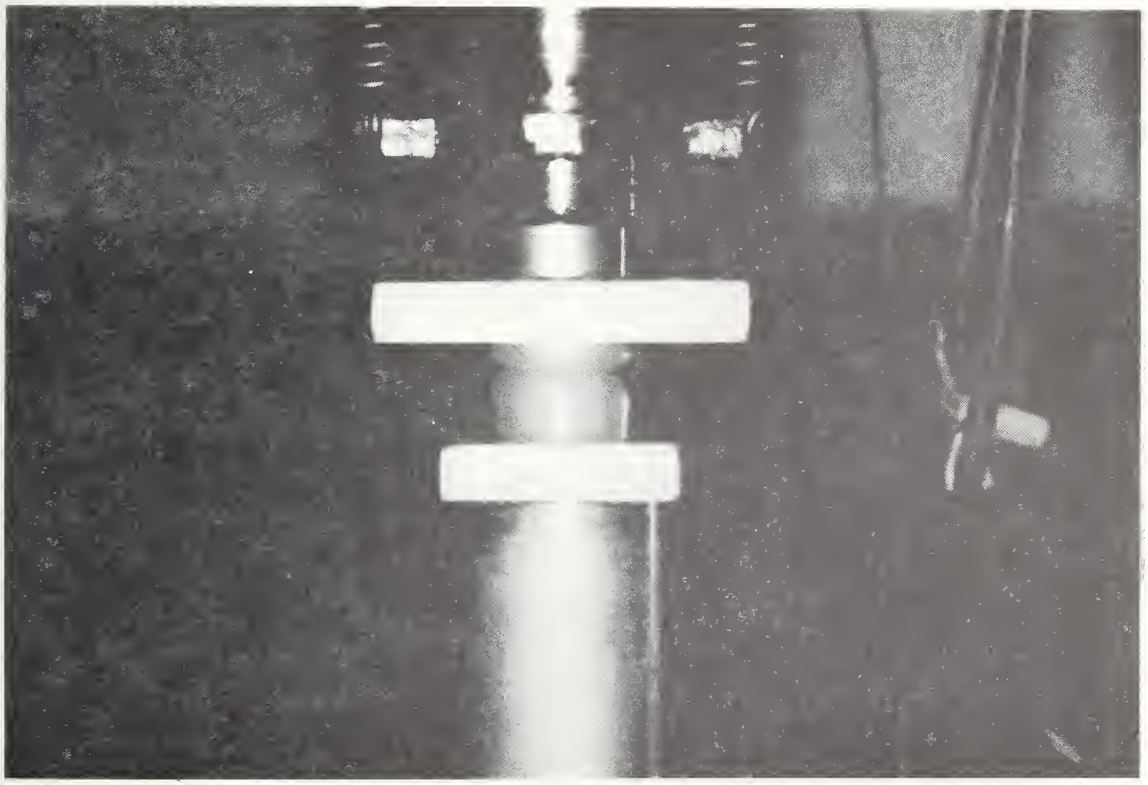


b.

Figure 4.5 -- Conical Secondary Spring Progressive Crush

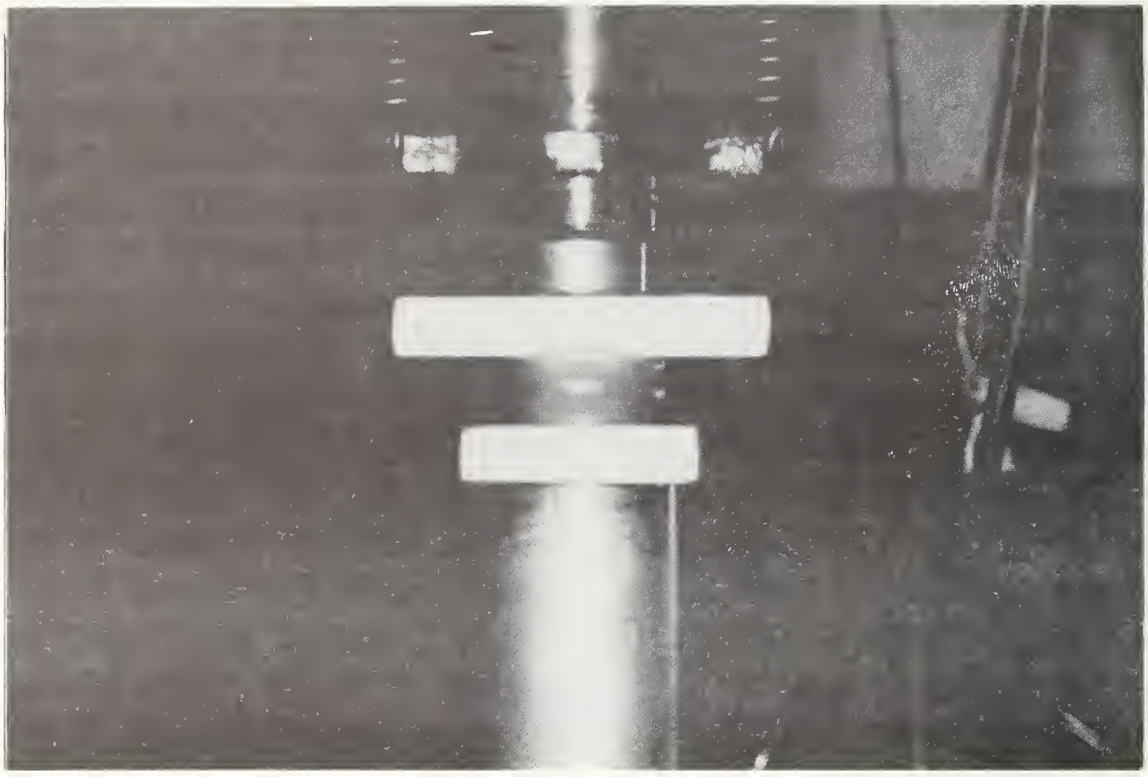


c.

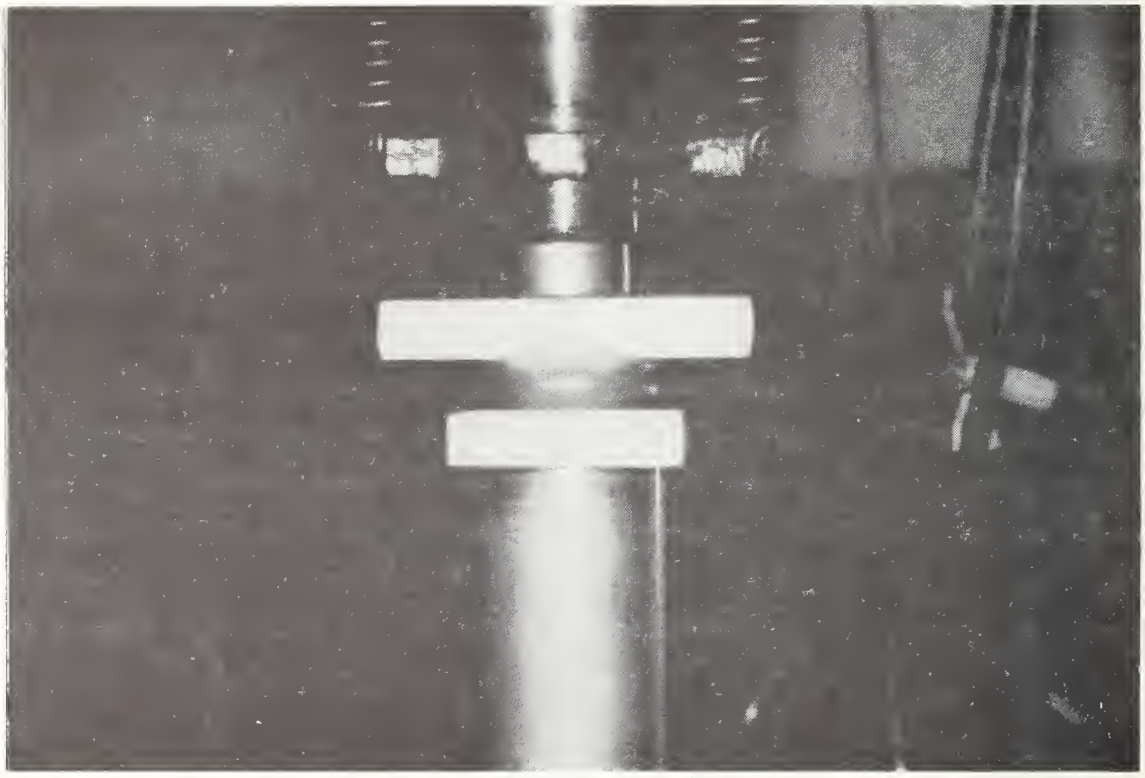


d.

Figure 4.5 (Continued) -- Conical Secondary Spring Progressive Crush



e.



f.

Figure 4.5 (Continued) -- Conical Secondary Spring Progressive Crush

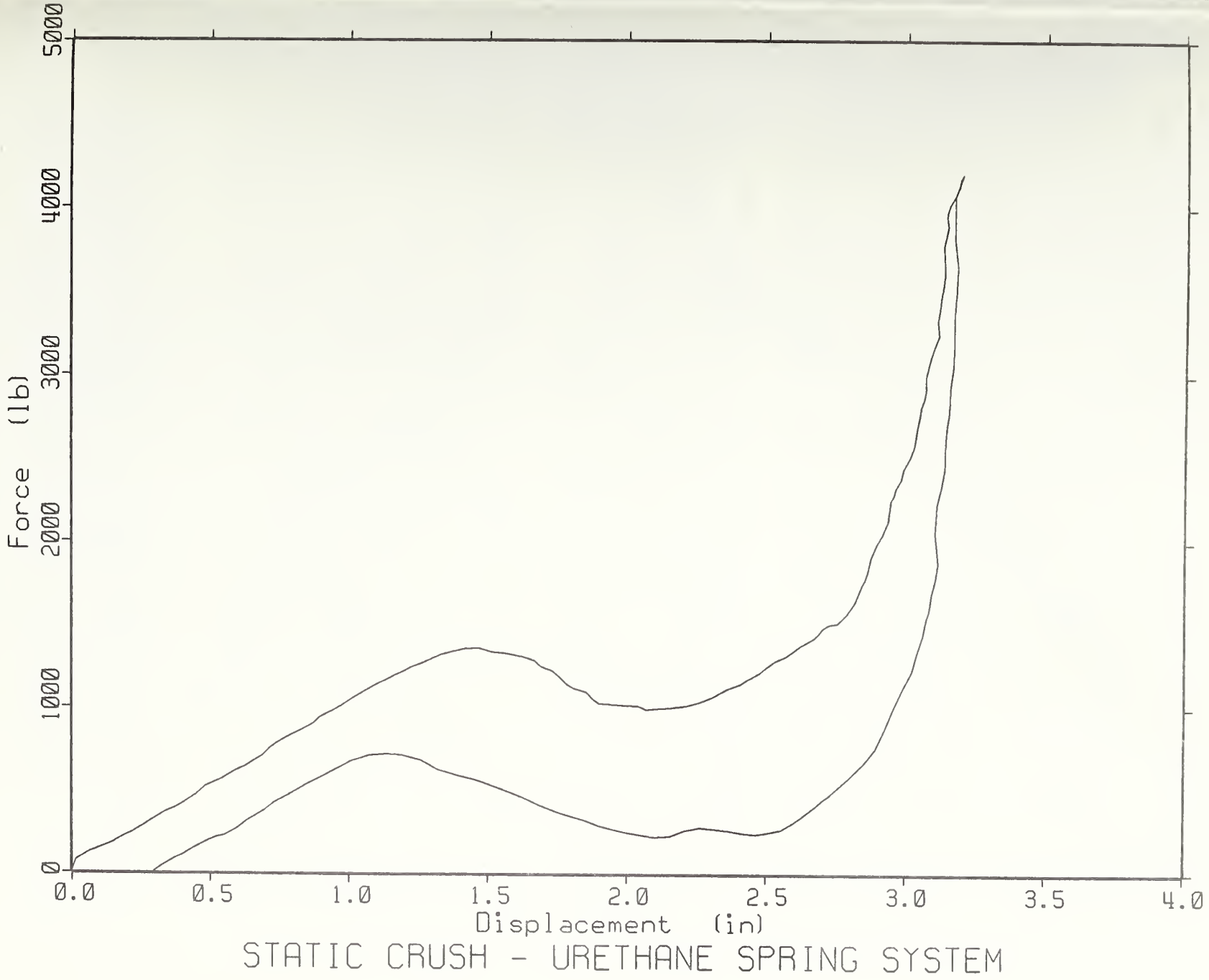

5000
4000
3000
2000
1000
0
Force (lb)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Displacement (in)
STATIC CRUSH - URETHANE SPRING SYSTEM

Figure 4.6

After the previously described tests were performed, as well as many others, the impactor was disassembled and inspected. It was found that the conical spring had been torn nearly in half at its mid-length. Note that this was the location of the 'necking in' described above. This spring was replaced and the calibration tests were repeated. The 1 meter drop speed test produced a force versus time trace very similar to that done previously (see Figure 4.7). The peak relative deflection for this test was 1.37" (34.8 mm), which was a little closer to the desired range, but still too high. The 2 meter drop speed test resulted in the force versus time curve shown in Figure 4.8. As can be seen, there was quite a difference from the original curve, with the center hump being exaggerated, peaking about 300 lbs (136 kg) higher than the original. Peak relative deflection for this test was 2.39" (60.7 mm), slightly lower than the original, but still half an inch over the specification.

Throughout all testing, two conical springs were torn, and a third damaged. A brief investigation led to the finding that the cone would deteriorate gradually from the inside surface. This degradation would become evident, if inspected, after very few impacts, but many were required to actually tear the cone. The severity of the impacts would determine the actual number it could withstand.

Partly due to the durability of the conical spring being of concern, a few tests were conducted which used an alternate spring/damper element. A thoracic impactor developed as part of another project at the Vehicle Research and Test Center (VRTC) (6) had good success with a spring/damper element made of Ethafoam 600, so this material was used. A schematic drawing of the modified impactor is shown in Figure 4.9. Essentially, the Urethane main spring was replaced by an Ethafoam 600 spring and the conical secondary spring was eliminated.

As with the original system, calibration tests were performed. The force/time trace from the 1 meter drop speed test is shown in Figure 4.10. As can be seen, it followed the corridor exceptionally well, remaining inside the limits the entire event. The results from the 2

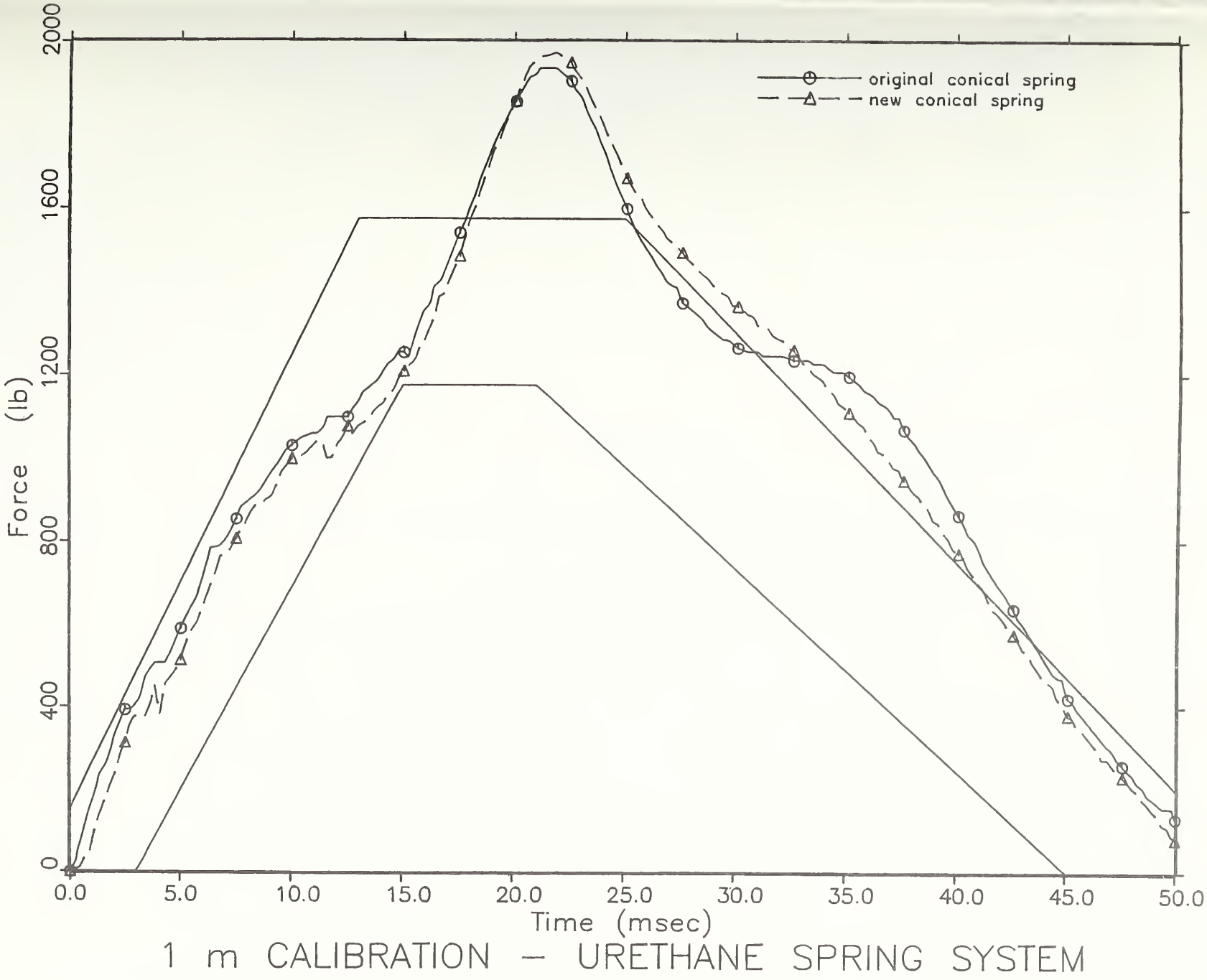

original conical spring
new conical spring
Force (lb)
2000
1600
1200
800
400
0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
Time (msec)
1 m CALIBRATION – URETHANE SPRING SYSTEM

Figure 4.7

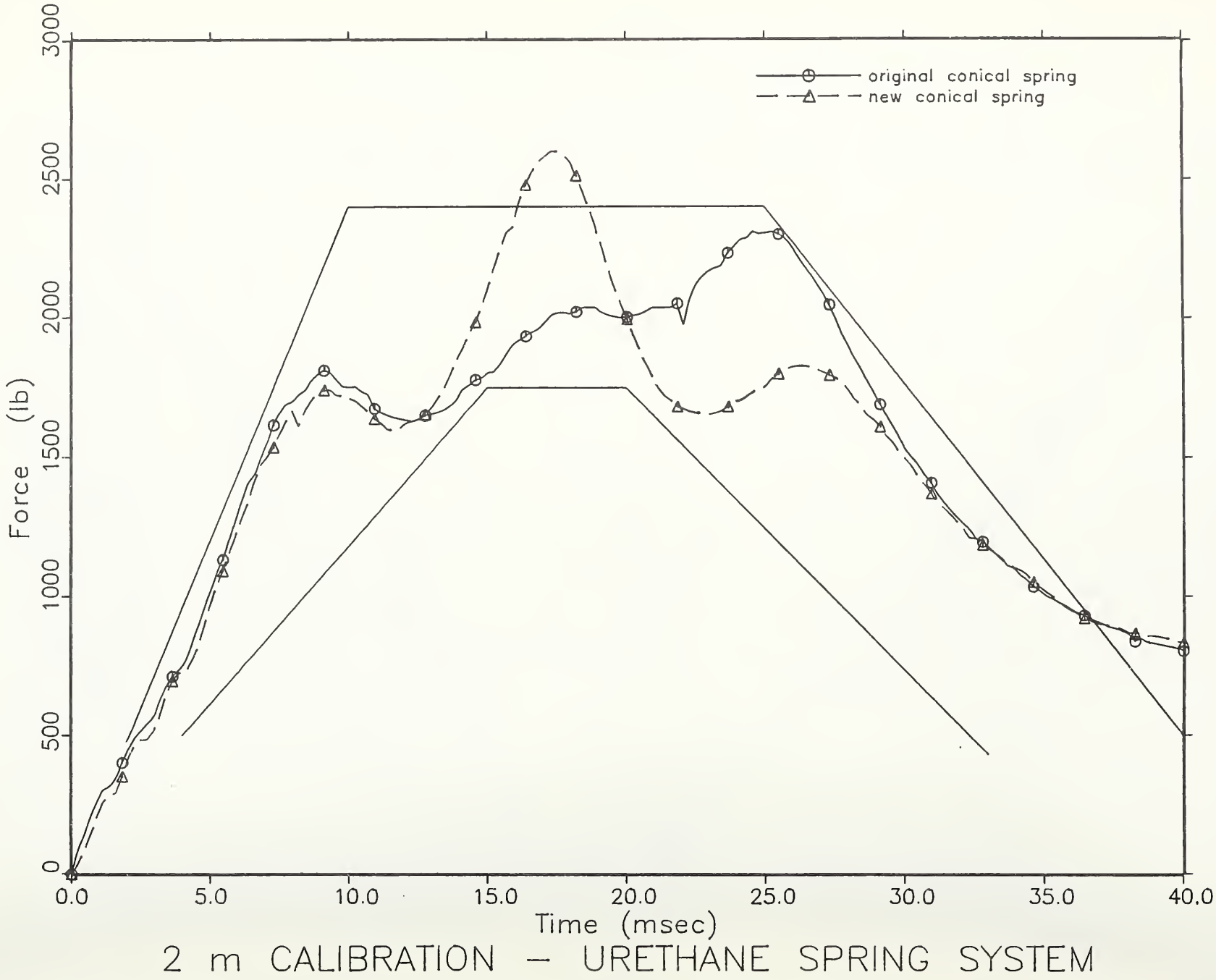

original conical spring
new conical spring
Force (lb)
0
500
1000
1500
2000
2500
3000
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
Time (msec)
2 m CALIBRATION — URETHANE SPRING SYSTEM

Figure 4.8

MVMA THORACIC IMPACTOR

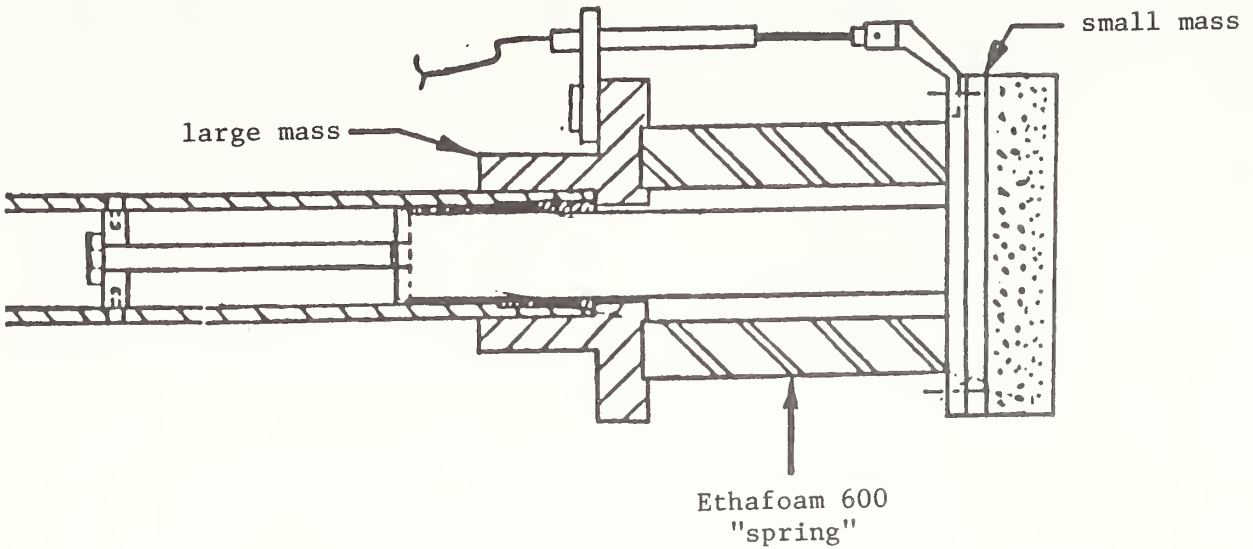


Figure 4.9

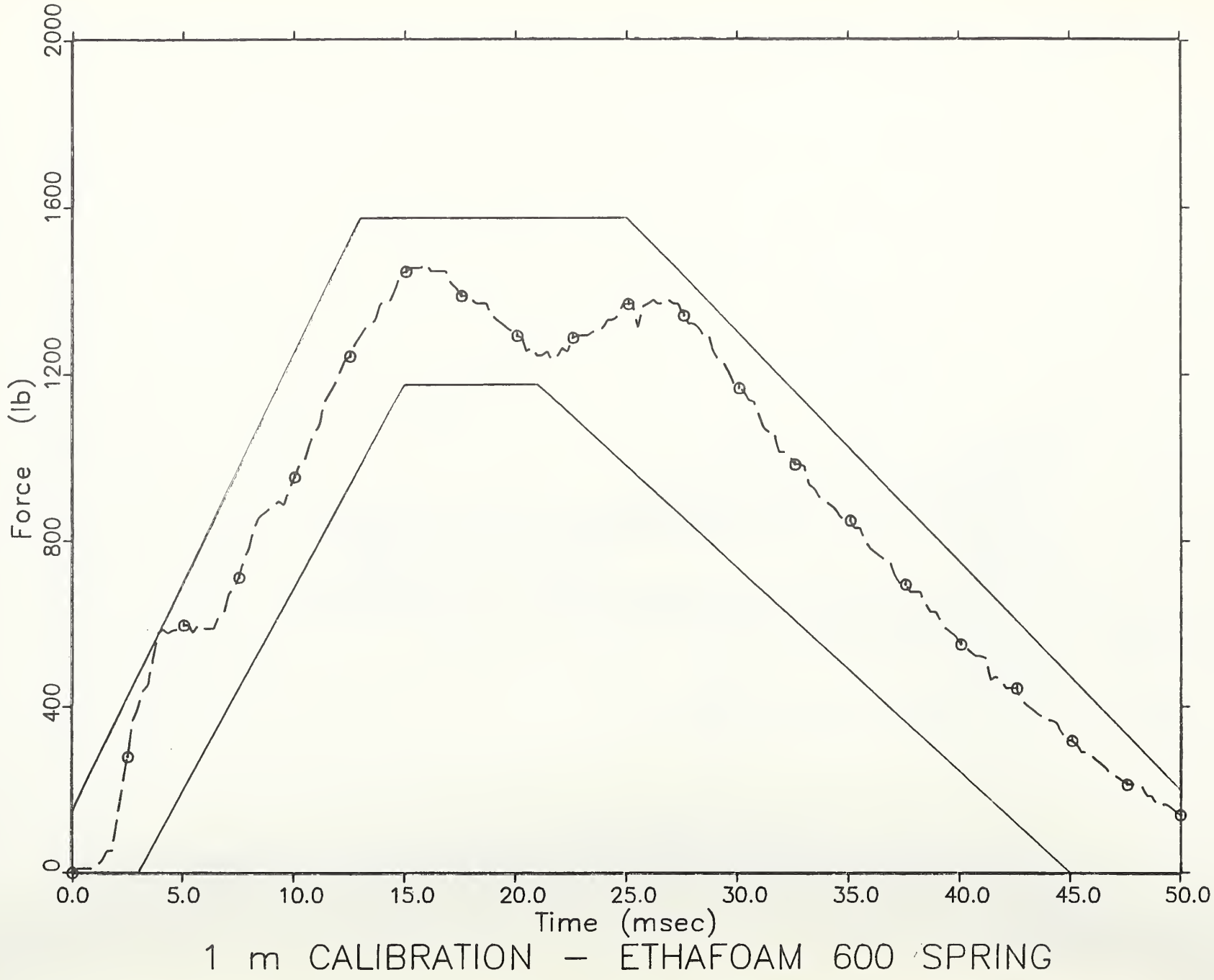

2000
1600
1200
800
400
0
Force (lb)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
Time (msec)
1 m CALIBRATION – ETHAFOAM 600 SPRING

Figure 4.10

meter drop speed test are shown in Figure 4.11. It also stayed within the corridor fairly well, dipping low during the rising portion, peaking about 50 lbs (23 kg) high, and falling back within the corridor during unloading. The peak relative deflections for these tests were 1.24" (31.5 mm) and 2.15" (54.6 mm), respectively. Note that the 1 meter drop speed test deflection was within the desired range while that of the 2 meter was high, although it was closer than that from the corresponding Urethane spring test.

Next, a static crush was done on the modified impactor (see Figure 4.12). Note that the Ethafoam 600 spring crushed in a uniform manner, without buckling. This resulted in the dashed force/deflection curve shown in Figure 4.13. Unlike with the Urethane/conical spring system, a continuously increasing curve was produced using the Ethafoam 600 spring, which was intuitively more satisfying.

As a final comparison, the relative deflections obtained from the impactor over a range of speeds were compared for the two spring/damper systems (see Figure 4.14). Both increased linearly through a range of impact speeds. The peak relative deflections from the Urethane spring tests began to level off at about 16 mph (25.7 km/h) while those using the Ethafoam 600 spring leveled off closer to 18 mph (29.0 km/h). The Ethafoam 600 typically deflected less for the same impact speed, until the two curves crossed a little under 17 mph (27.4 km/h), corresponding to a deflection of about 2.9" (73.7mm). One further observation worth noting was that unlike the Urethane spring, the Ethafoam 600 needed up to an hour to fully recover from impacts at the higher speeds.

4.3 General Hardware Systems

An agreement was made that VRTC personnel would provide the MVMA with observations and experience regarding the mechanical aspects of the device. Overall, the hardware systems functioned very well. With the exception of the problems with the conical spring detailed in the

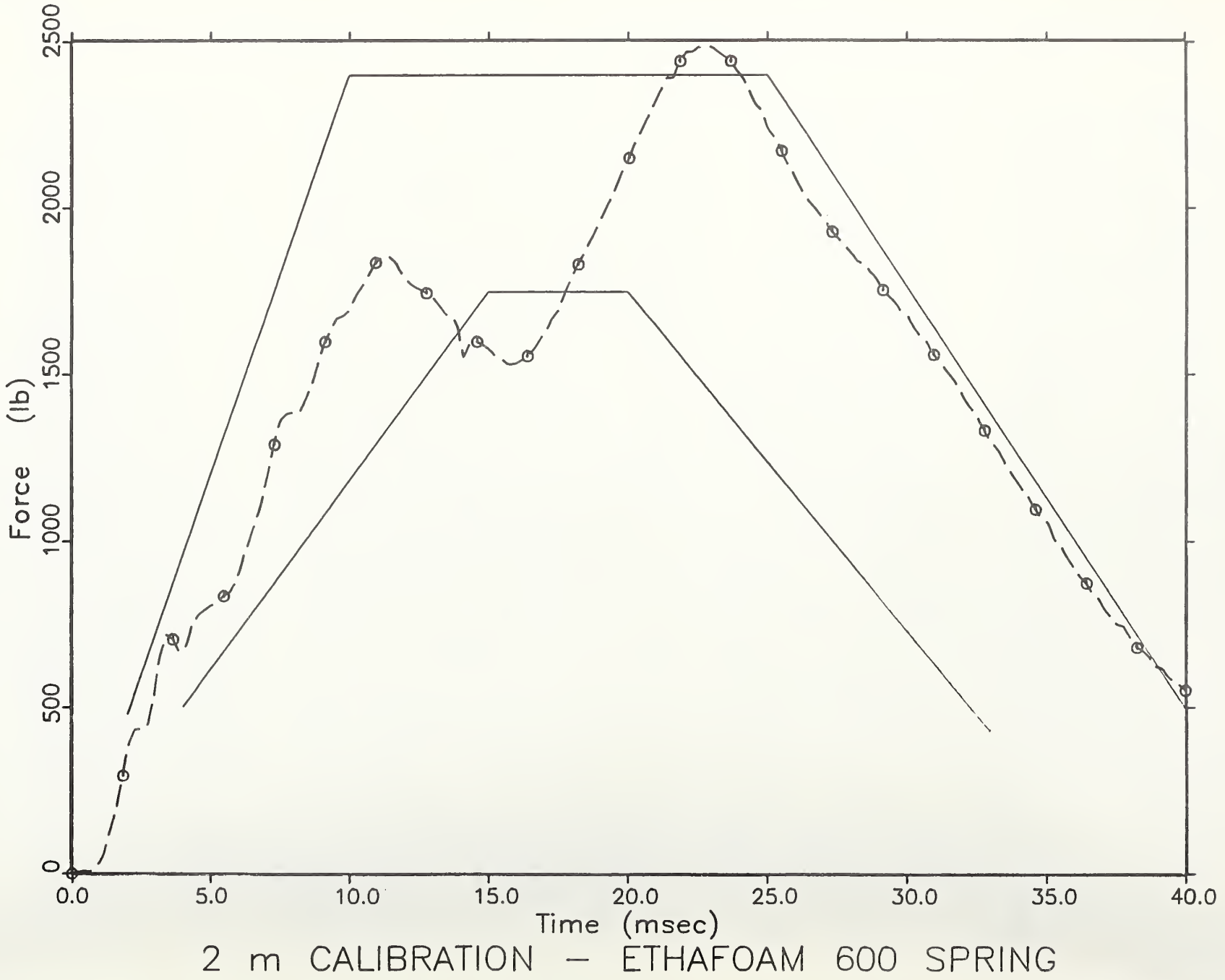
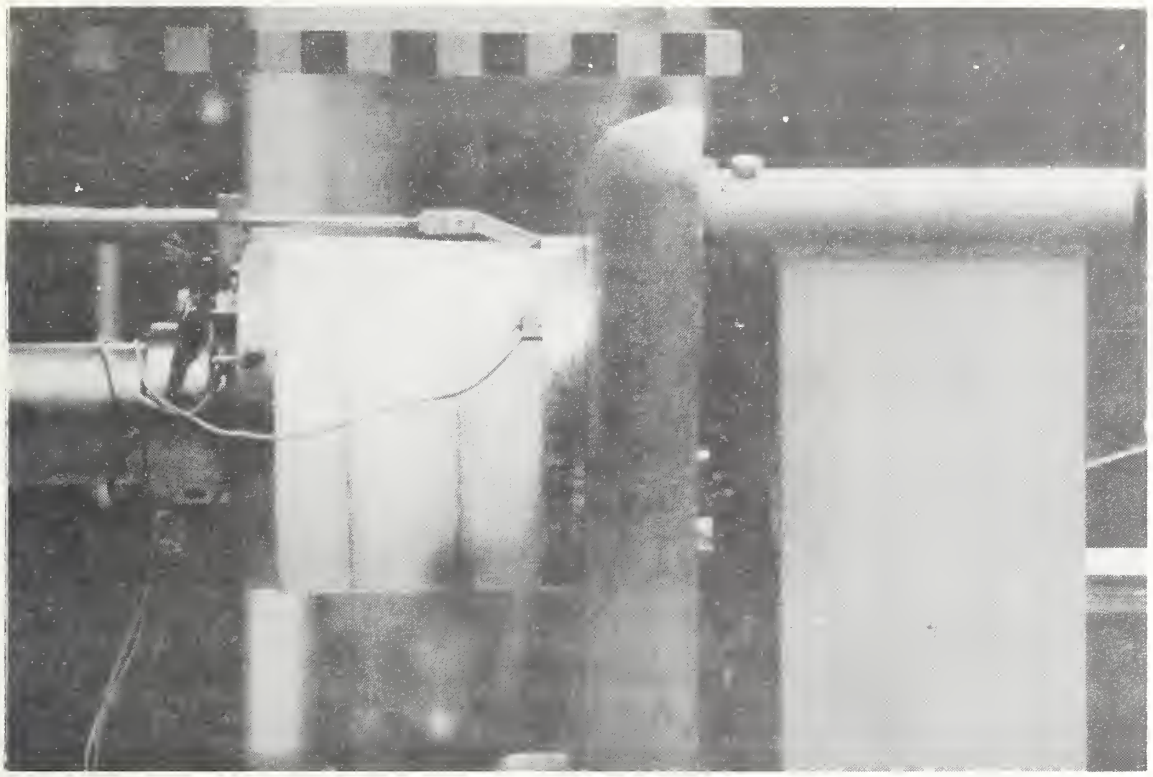
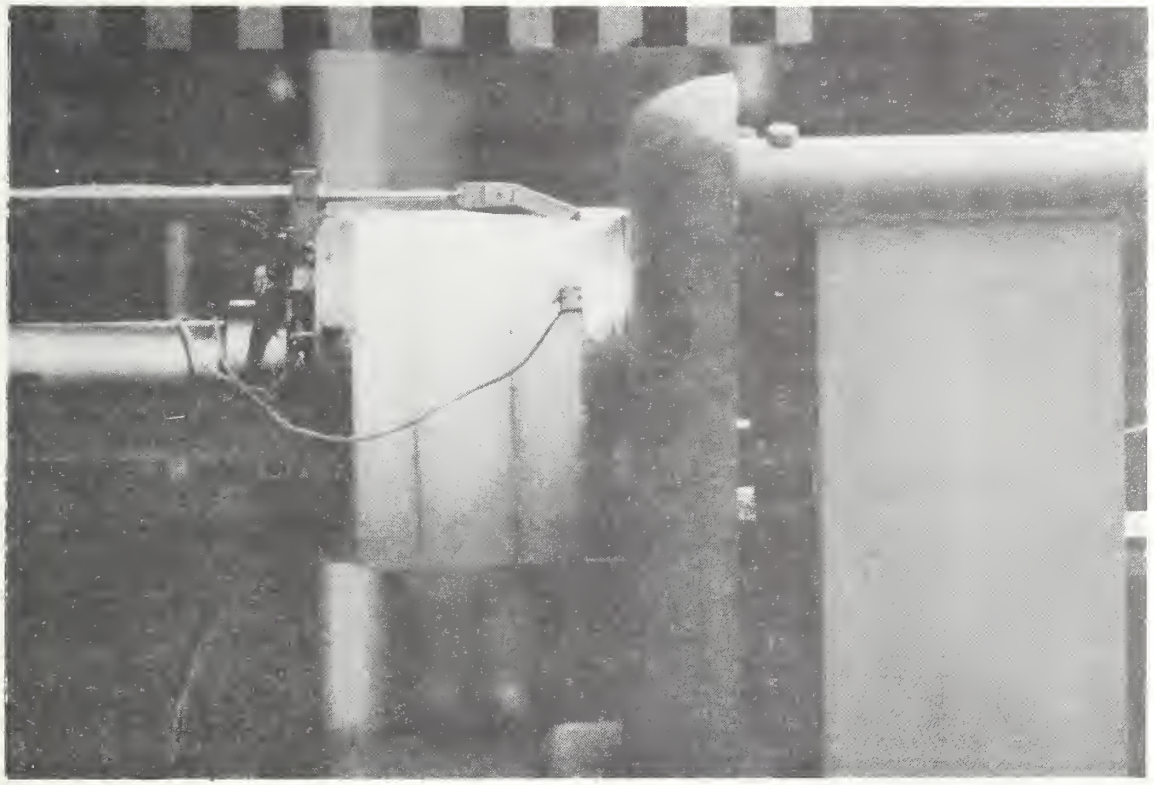

2500
2000
1500
1000
500
0
Force (lb)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
Time (msec)
2 m CALIBRATION — ETHAFOAM 600 SPRING

Figure 4.11

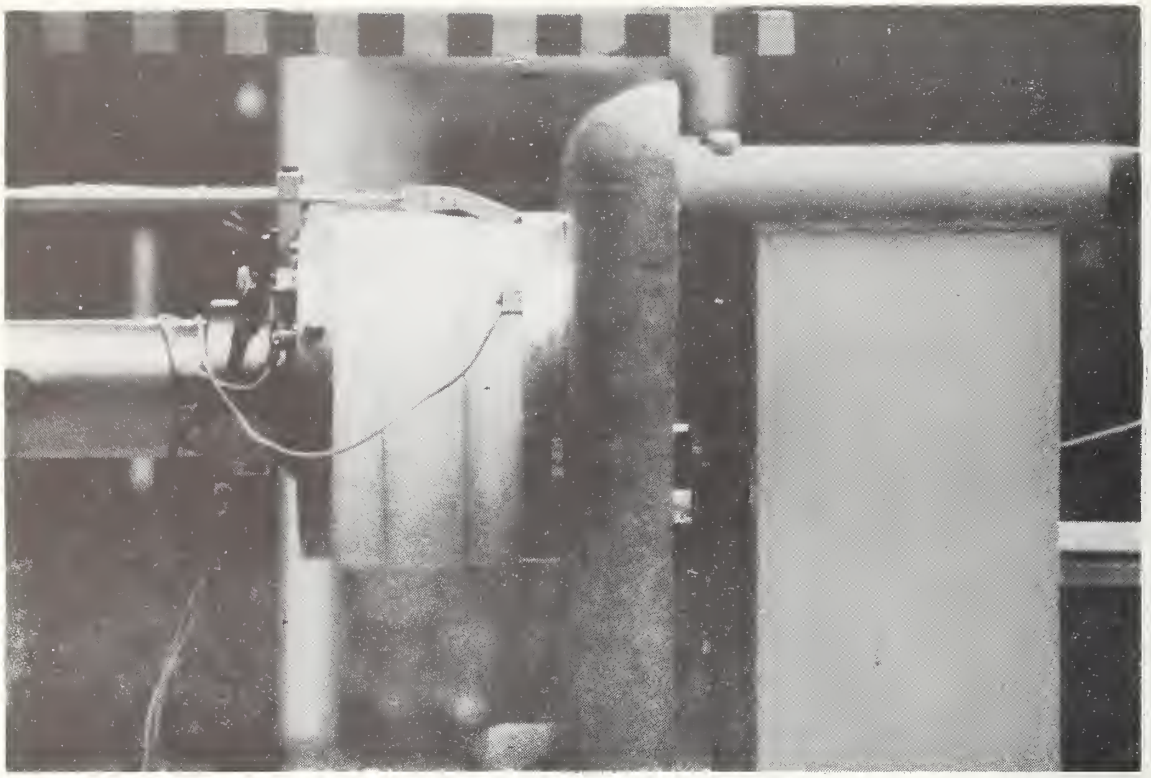


a. 0"

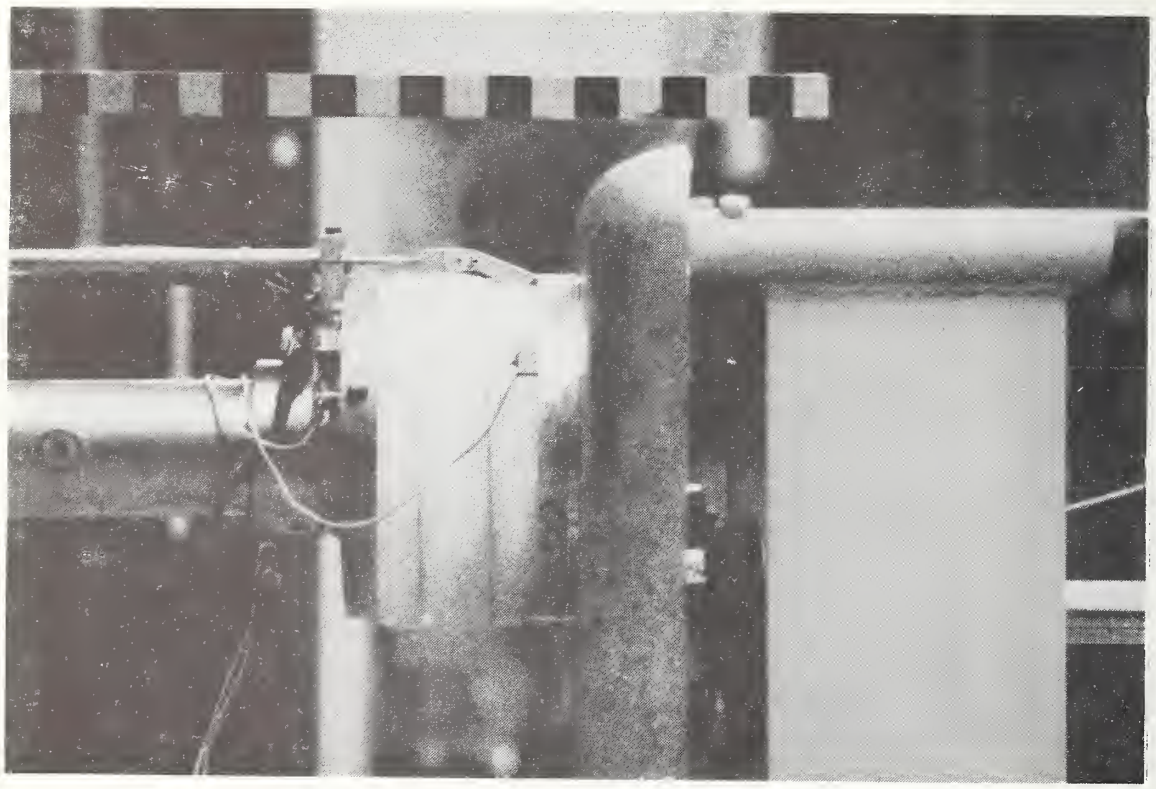


b. 1"

Figure 4.12 -- Ethafoam 600 Spring -- Progressive Crush

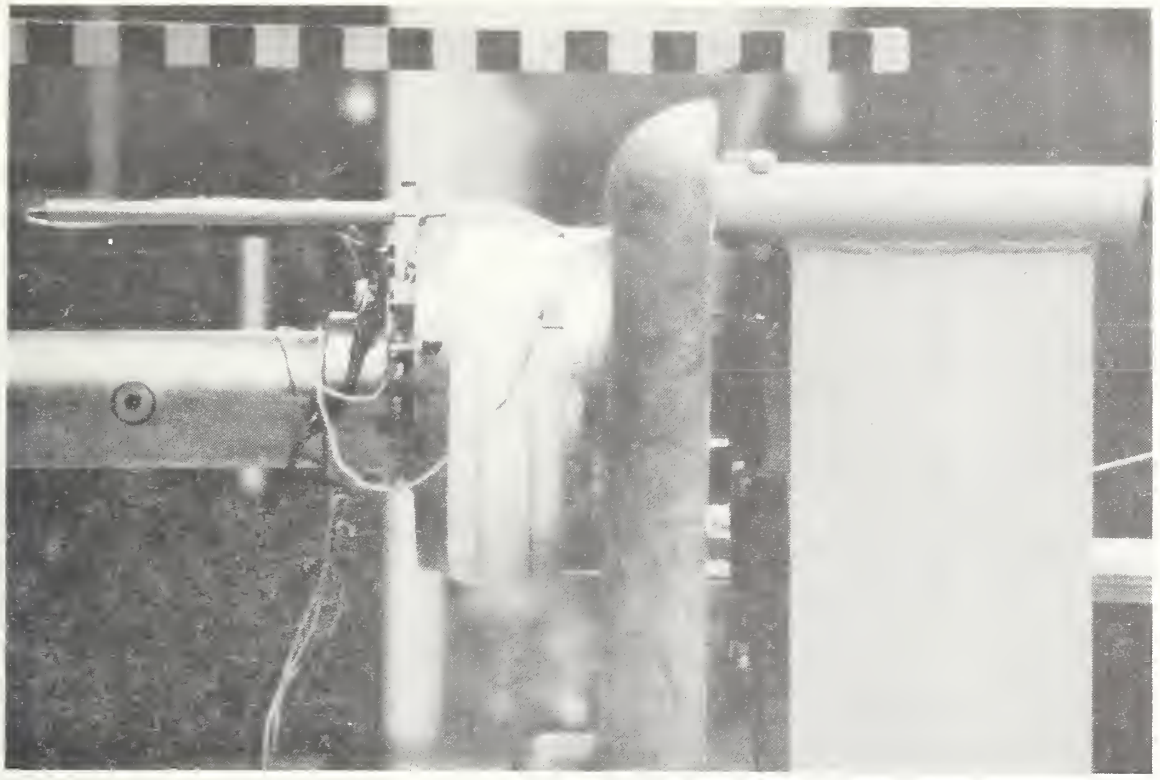


c. 1-3/4"



d. 2-1/2"

Figure 4.12 (Continued) -- Ethafoam 600 Spring -- Progressive Crush



e. 3-1/2"

Figure 4.12 (Continued) -- Ethafoam 600 Spring -- Progressive Crush

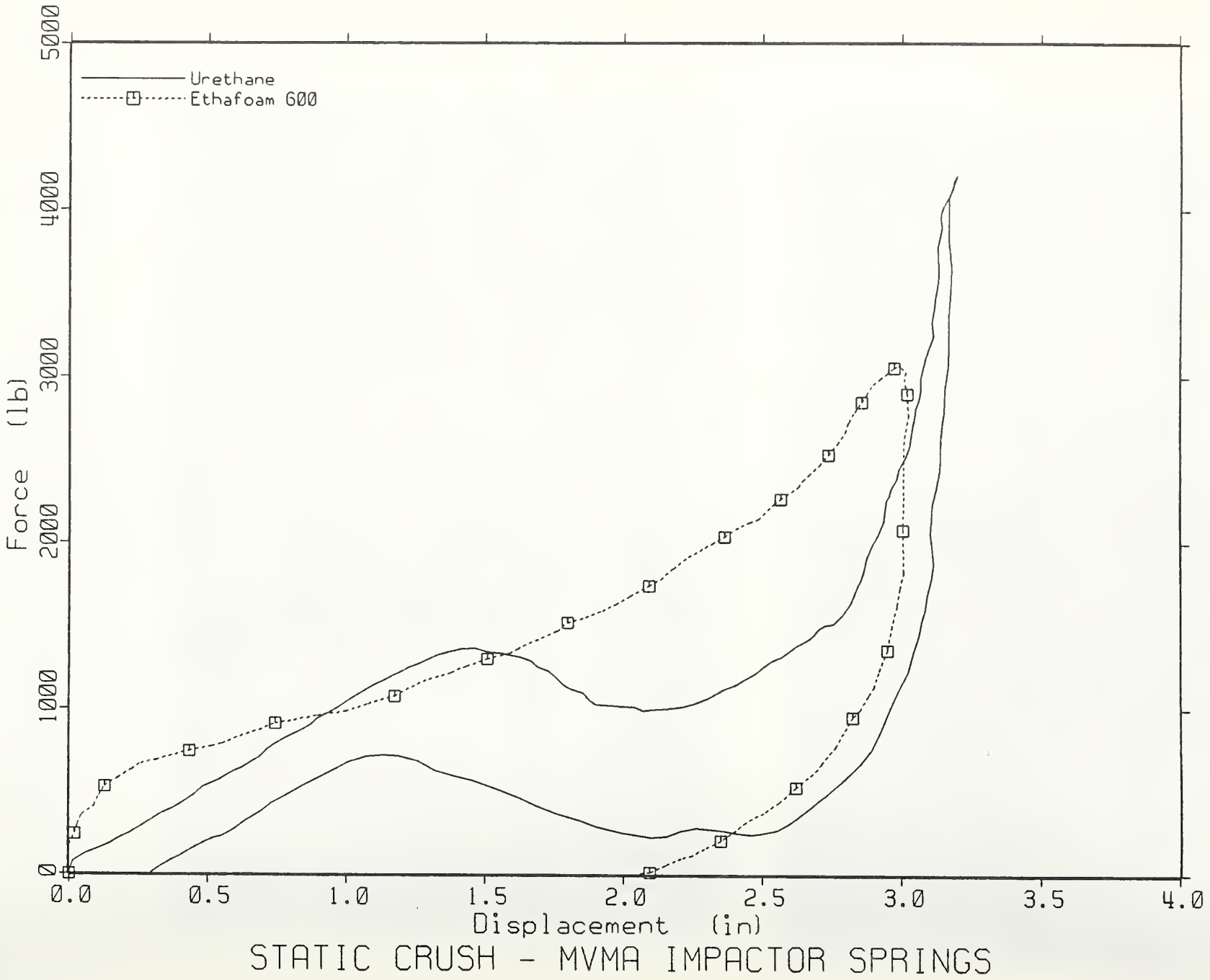

Urethane
Ethafoam 600
Force (lb)
0
1000
2000
3000
4000
5000
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Displacement (in)
STATIC CRUSH - MVMA IMPACTOR SPRINGS

Figure 4.13

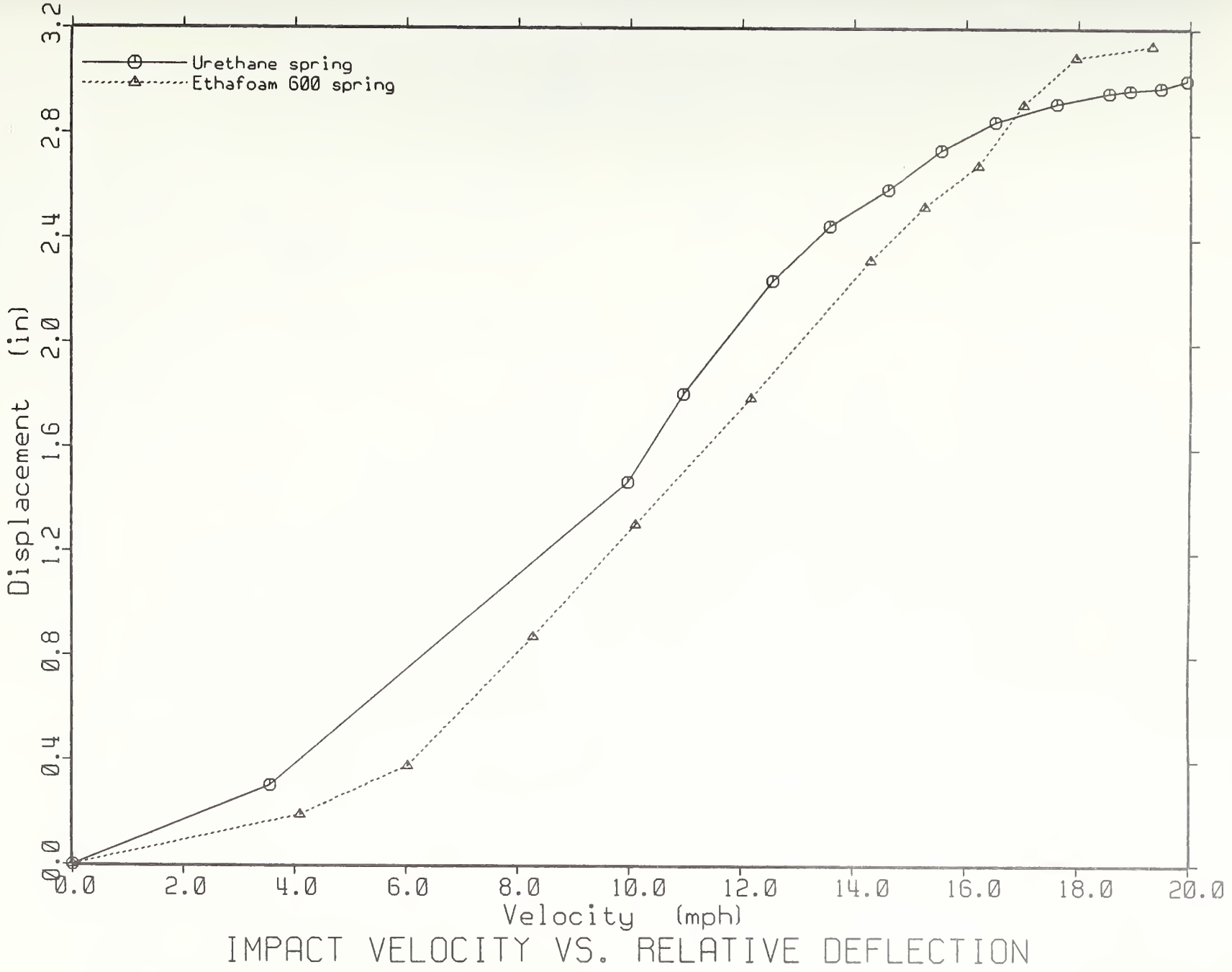

Urethane spring
Ethafoam 600 spring
Displacement (in)
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
Velocity (mph)
IMPACT VELOCITY VS. RELATIVE DEFLECTION

Figure 4.14

previous section, the device was very durable, with no breakdowns. Two areas of concern arose, though.

First, in essentially all the tests, a mechanical 'ringing' occurred on the large mass signal shortly after impact (see Figure 4.15). Since this ringing was of high frequency and occurred before the main peak of the impact, it had no effect on the filtered peak value. Due to time constraints, no effort to solve this problem was made, but a potential source of this ringing was noted.

Part of the large mass was a collar which mounted on the end of the main tube and served as the rear mating surface for the Urethane spring. This component is shown in Figure 4.1, identified by the large cross-hatching, slanting down from right to left. This collar attached to the tube by means of four set screws which tightened to the tube. The indentations made from these screws were found to be elongated, assumably from repeated impacts. It was felt that the movement of these screws within the elongated holes could have caused the ringing, although this was not verified.

The second area of concern involved the relative deflection between the large and small masses. Frequently, this deflection flattened near the peak, as seen in Figure 4.16. Since this happened at various levels of deflection, it was not due to overscaling the instruments or data acquisition components. Although not verified, it was felt that this flattening was a real occurrence, possibly due to friction. The effect that this has on the device's ability to measure injury potential likely depends on the criterion used. Obviously, responses based on peak relative deflections would be expected to be in error. On the otherhand, since both peak accelerations and peak velocity occur prior to this flattening, and since the exact cause of this occurrence was not determined, it is impossible to determine what, if any, effect it would have on acceleration and velocity based responses.

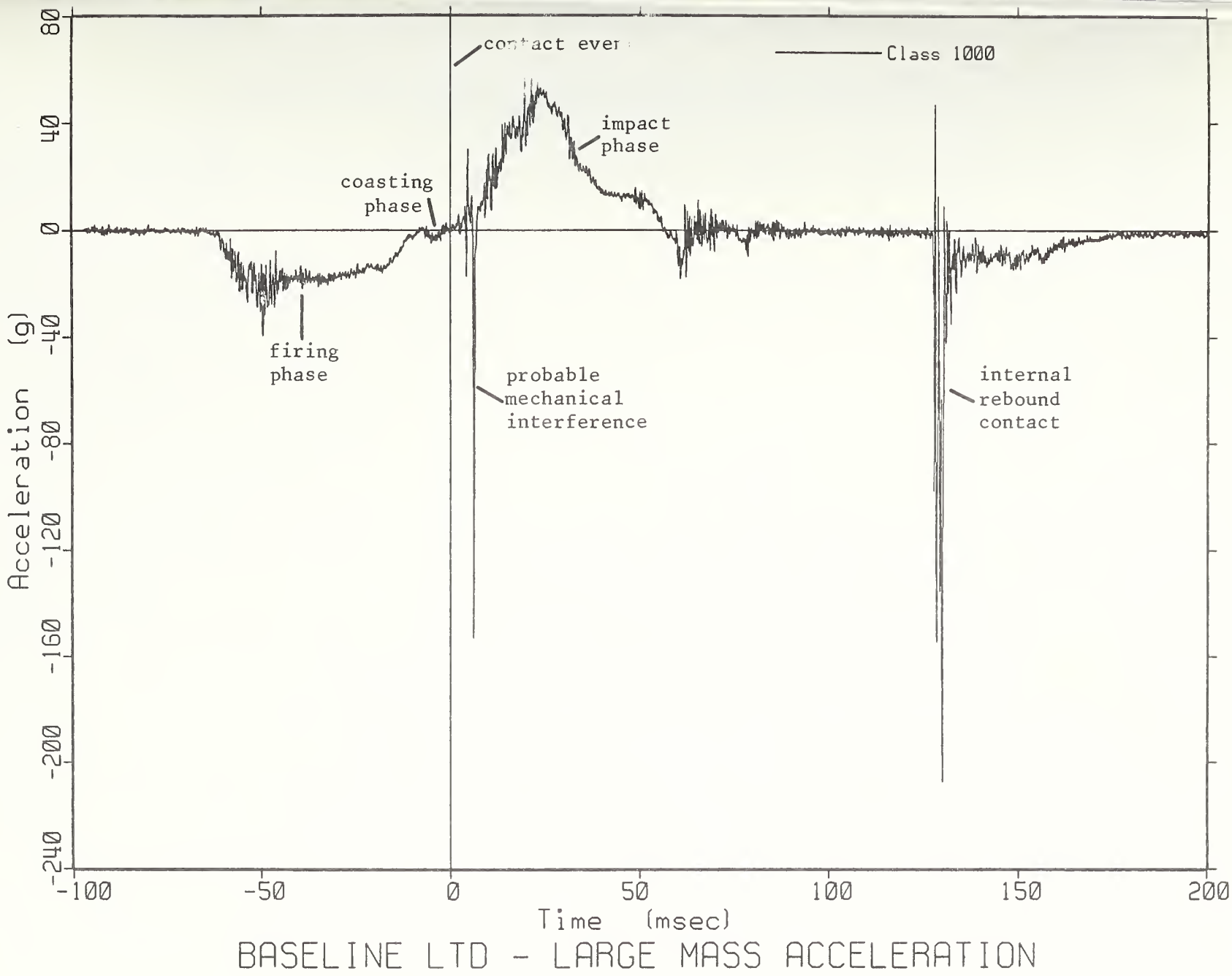

contact event
Class 1000
impact phase
coasting phase
firing phase
probable mechanical interference
internal rebound contact
Acceleration (g)
80
40
0
-40
-80
-120
-160
-200
-240
-100
-50
0
50
100
150
200
Time (msec)
BASELINE LTD - LARGE MASS ACCELERATION

Figure 4.15

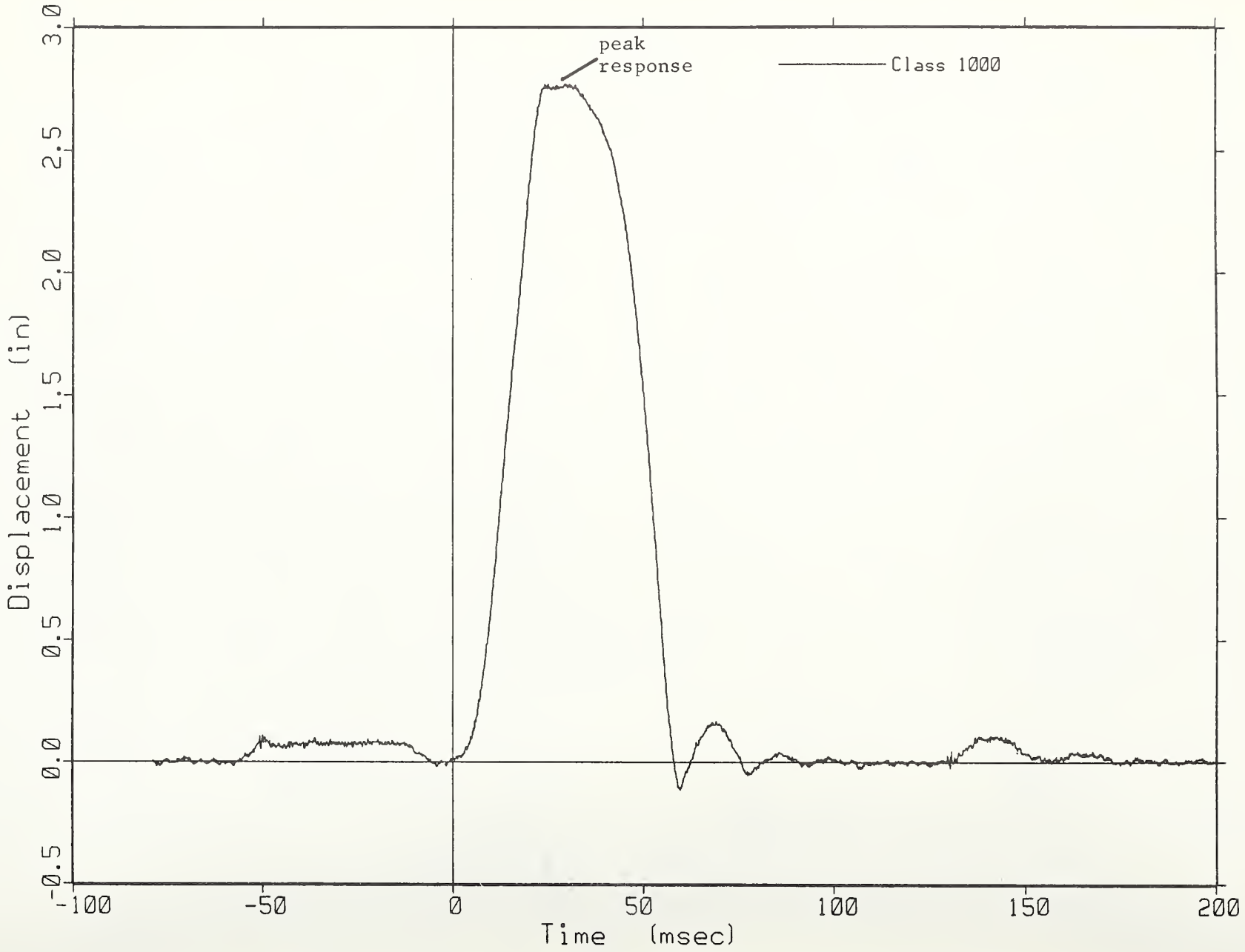

peak
response
Class 1000
Displacement (in)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-100
-50
0
50
100
150
200
Time (msec)
BASELINE LTD - RELATIVE DEFLECTION

Figure 4.16

One final aspect of the device that was investigated was its ability to repeat an impact speed when charged to the same pressure. A series of tests was run at the beginning of the program, recording both speed and pressure. These are plotted with circles in Figure 4.17. Three tests from the later portion of the program were then added to this curve and are shown in the figure by triangles. As can be seen, all but the 18 mph (29.0 km/h) test fell right on the curve, with that test requiring about an 8% increase in pressure to achieve the same speed as indicated by the curve. Overall, the performance of the device was very good.

4.4 Software Systems

In addition to the mechanical device, the MVMA Thoracic Impactor also consisted of an electronic control system, a data acquisition system, and an operating program, run on an IBM PC, which included data processing routines. The correct operation of these components was as important as that of the hardware.

The operating program did a good job of coordinating the functions of the control and data acquistion systems. For the most part it was menu driven and easy to follow, with error recovery if an incorrect character was entered. This program also contained data processing and plotting routines, which also had good utility.

The control system was organized in a straight forward manner, but problems were frequently encountered. Often, a light would flash, the alarm would sound, gas would escape, or some other unexpected occurrence would take place. Invariably, this locked up the operating program and the only way to proceed was to exit from the program and begin again. At times it was necessary to re-boot the PC. A pattern or a cause for this happening was never found, but the safeties worked well. Throughout all the testing, none of these problems caused the impactor to fire prematurely.

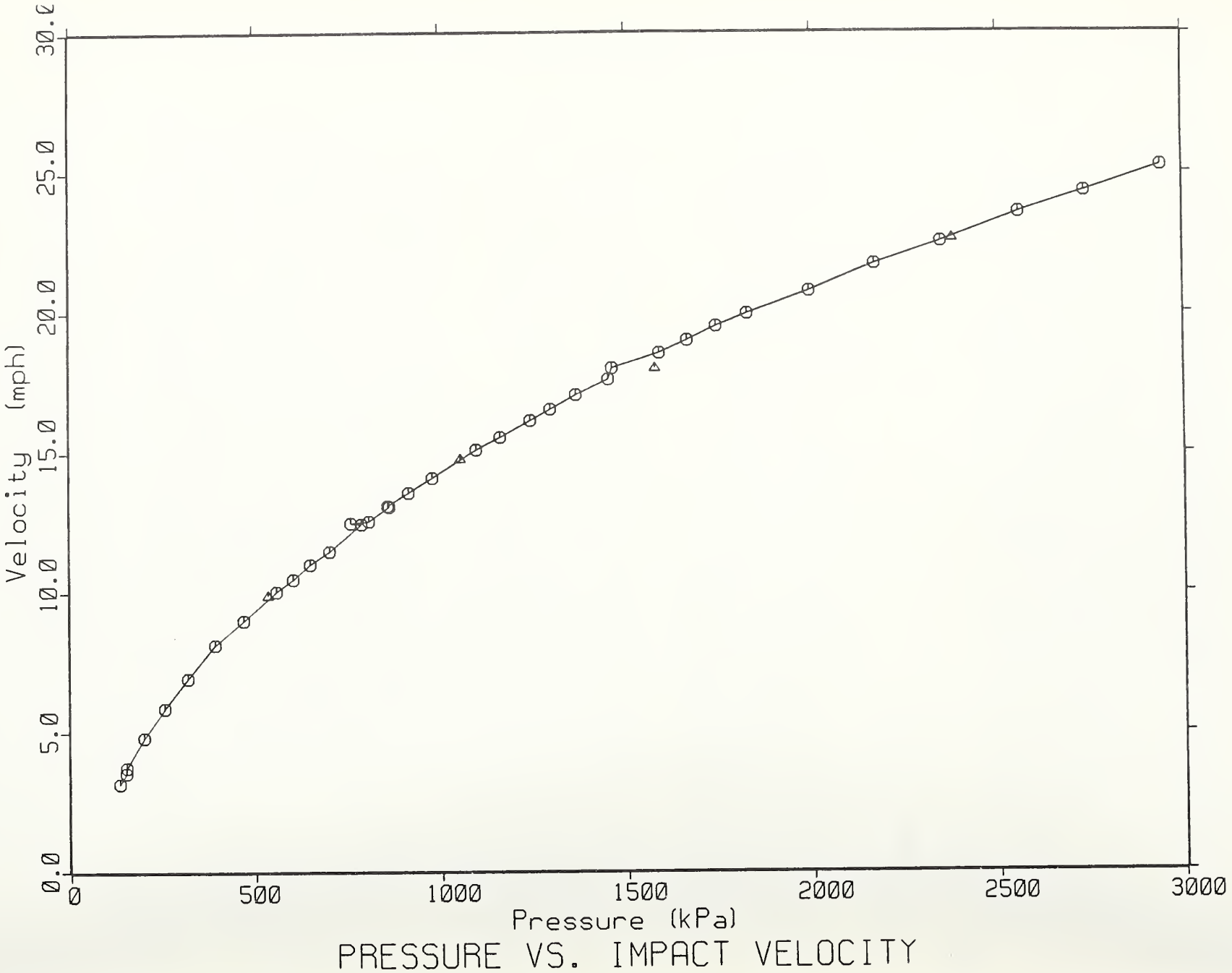

Velocity (mph)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
0
500
1000
1500
2000
2500
3000
Pressure (kPa)
PRESSURE VS. IMPACT VELOCITY

Figure 4.17

The data acquistion system performed very well, causing no problems during testing. No data was lost and the system interacted smoothly with the operating program. The only shortcoming was that it had a sampling rate of about 4400 Hz, which was too slow to be compatible with the Class 1000 filter applied to the data. To avoid aliasing, the recommended sampling rate should be about five times the cutoff frequency of the filter used. For a Class 1000 filter, a sampling rate of at least 8000 Hz is recommended. For the purposes of this investigation, parallel instrumentation was added to the impactor. The data from these transducers were collected through the VRTC data acquisition system, which used a sampling frequency of 8000 Hz. These data were used for the evaluation of the impactor.

5.0 TEST METHODOLOGY COMPARISON

5.1 Test Results

As mentioned previously, the most crucial aspect of this program was to evaluate the ability of the device and its associated procedures to assess the thoracic injury potential of vehicles. This included performing three series of tests, two using the full body of the vehicles, the third testing the doors mounted in a fixture. In addition, one padded test was done to estimate the benefit from 3" (76 mm) of ArCel padding, using the impactor. Table 5.1 is a matrix of the tests done for these series. The results from the three series of tests are listed in Tables 5.2 through 5.4.

5.2 Comparison of Results

5.2.1 Padding Effects

As shown in Table 5.1, baseline and padded Granada tests were conducted. The purpose of these was to estimate the benefit from 3" (76 mm) of ArCel padding, using the impactor. The peak accelerations, peak relative deflections, and peak Viscous Criterion (7), or V*C, for these two tests are compared in Table 5.5. Overlay plots of these responses

Table 5.1
MVMA THORACIC IMPACTOR TEST MATRIX

Vehicle	Full-Body		Fixtured Door
	18 mph	adjusted	18 mph
Celebrity			
Citation			
Dodge 400			
Granada	*		
Horizon			
bas LTD			
mod LTD			----
Rabbit			
Spectrum	----		

* repeated with 3" of ArCel padding

Table 5.2
MVMA THORACIC IMPACTOR TEST RESULTS
Full-Body Test Series No. 1 - 18 mph
VRTC-86-0025

Vehicle	Test Number	Actual Impact Velocity (mph)	Peak Acceleration (g)		TTI			Peak Relative Deflection		VC(max)	
			sm mass (rib)	lg mass (T12)	age 0	age 23	age 41	(in)	(msec)	(m/sec)	(msec)
Celebrity	P25018	18.0	118.6	44.4	81.5	113.7	138.9	2.48	27.000	1.035	22.625
Citation	P25001	17.7	94.2	41.4	67.8	100.0	125.2	2.35	30.625	0.747	15.375
Dodge 400	P25006	17.9	55.2	48.8	52.0	84.2	109.4	2.58	34.250	0.871	24.250
Granada (baseline)	P25013	18.0	71.7	51.3	61.5	93.7	118.9	2.60	35.125	0.973	20.625
Granada (padded)*	P25017	18.0	43.0	31.2	37.1	69.3	94.5	2.18	39.250	0.426	32.375
Horizon	P25011	18.0	92.8	35.7	64.3	96.5	121.7	2.22	32.500	0.763	27.875
bas LTD	P25019	17.9	72.5	50.6	61.6	93.8	119.0	2.63	32.125	1.279	19.875
mod LTD	P25020	17.8	73.7	53.3	63.5	95.7	120.9	2.67	29.625	1.307	17.625
Rabbit	P25021	18.0	77.3	59.2	68.3	100.5	125.7	2.67	30.750	1.237	18.250

* Granada padded test was done on a new door and at the same location as Granada unpadded test.

Table 5.3
MVMA THORACIC IMPACTOR TEST RESULTS
Fixtured Door Tests - 18 mph
VRTC-86-0025

Vehicle	Test Number	Actual Impact Velocity (mph)	Peak Acceleration (g)		TTI			Peak Relative Deflection		VC(max)	
			sm mass (rib)	lg mass (T12)	age 0	age 23	age 41	(in)	(msec)	(m/sec)	(msec)
Celebrity	P25036	18.1	113.9	50.5	82.2	114.4	139.6	2.83	26.750	1.202	20.625
Citation	P25038	18.0	116.1	46.0	81.1	113.3	138.5	2.88	22.875	1.361	17.500
Dodge 400	P25030	17.7	53.2	35.6	44.4	76.6	101.8	1.66	38.750	0.384	15.250
Granada	P25028	17.7	48.2	33.2	40.7	72.9	98.1	1.38	36.250	0.250	14.000
Horizon	P25039	18.0	96.0	44.8	70.4	102.6	127.8	2.51	33.000	0.733	15.000
LTD	P25040	18.0	83.0	41.3	62.2	94.4	119.6	2.21	32.625	0.533	13.500
Rabbit	P25031	18.0	127.2	63.4	95.3	127.5	152.7	2.81	22.250	1.292	16.000
Spectrum	P25035	18.1	73.9	40.4	57.2	89.4	114.6	1.94	34.500	0.524	14.000

Table 5.4
MVMA THORACIC IMPACTOR TEST RESULTS
Full-Body Test Series No. 2 - adjusted velocities
VRTC-86-0025

Vehicle	Test Number	Impact Velocity (mph)		Peak Accel. (g)		TTI			Peak Relative Deflection		VC(max)		Crash Tests TTI
		intended	actual	sm mass (rib)	lg mass (T12)	age 0	age 23	age 41	(in)	(msec)	(m/sec)	(msec)	age=0
Celebrity	P25045	17.9	17.86	111.9	39.9	75.9	108.1	133.3	2.40	30.625	0.827	26.625	79.0
Citation	P25044	18.0	17.97	80.9	43.8	62.4	94.6	19.8	2.70	32.750	0.875	23.125	89.5
Dodge 400	P25046	18.5	18.36	90.4	42.7	66.6	98.8	124.0	2.51	36.375	0.867	27.375	118.5
Granada	P25051	17.9*	22.63*	119.4	92.4	105.9	138.1	163.3	2.92	23.000	1.733	19.875	102.5
Horizon	P25049	18.8	18.97	100.9	41.7	71.3	103.5	128.7	2.66	30.125	1.094	25.250	111.5
bas LTD	P25050	18.5	18.40	66.8	54.5	60.7	92.9	118.1	2.77	24.125	1.287	19.000	98.5
mod LTD	P25054	14.8	14.78	56.2	38.5	47.4	79.6	104.8	2.28	32.625	0.613	27.000	83.5
Rabbit	P25047	18.9	18.74	68.5	61.9	65.2	97.4	122.6	2.73	25.375	1.242	19.875	115.5
Spectrum	P25048	19.0	19.07	74.2	61.5	67.9	100.1	125.3	2.84	24.375	1.350	19.125	83.5

* This test was intentionally conducted at a higher speed. See discussion in section 5.2.3

for the two tests are shown in Figures 5.1 through 5.4. Note that the largest peak of the baseline small mass acceleration occurred at about 60 msec. This was due to the small mass rebounding into the large mass and was therefore not considered to be the peak small mass response.

Table 5.5
18 mph FORD GRANADA TEST RESULTS
padded vs. baseline

Door Condition	Peak Acceleration		TTI(0)	Peak Relative Deflection (in)	VC(max) (m/sec)
	sm mass (rib)	lg mass (T12)			
baseline	71.7	51.3	61.5	2.60	0.973
padded	43.0	31.2	37.1	2.18	0.426

As can be seen in the table and figures, 3" (76 mm) of ArCel padding had the following effect on the responses measured by the impactor: peak small mass and large mass accelerations were reduced by 40% and 39%, respectively, resulting in a 40% reduction of TTI(age=0), and peak relative deflection and peak V*C decreased 16% and 56%, respectively.

5.2.2 Comparison of Sub-system Approaches

Another aspect of this study was to compare two different sub-system test procedures. This was done using the results of the full-body tests performed in test series 1 and those of the fixtured door tests, since both were conducted using a nominal impact speed of 18 mph (29.0 km/h). Comparisons were made between peak accelerations, peak relative deflections, peak V*C, static crush curves, and overall deformation of the doors.

In many cases, the crush pattern on the fixtured door was very different from that mounted in the body. Overhead views of the crushed

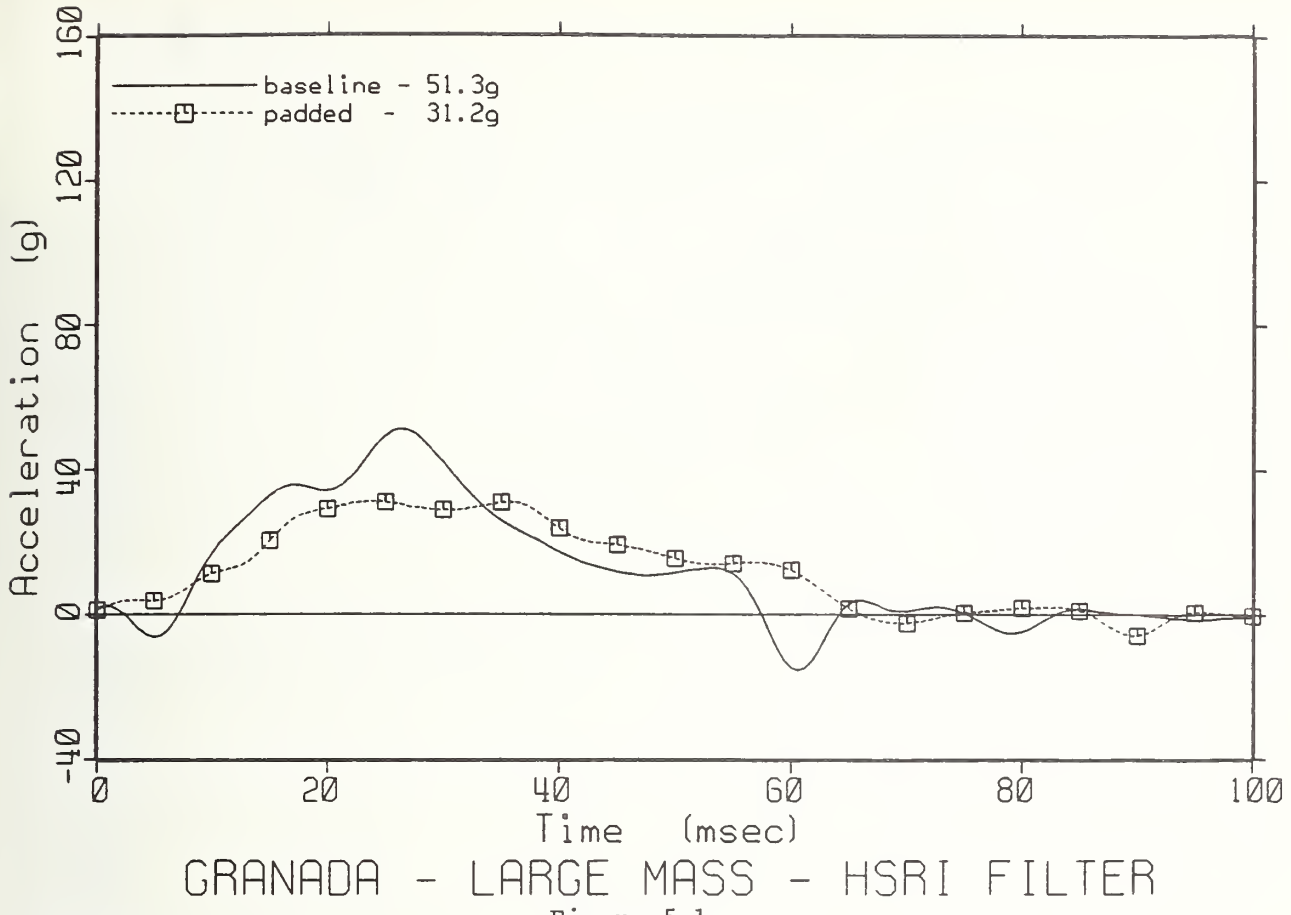


Figure 5.1

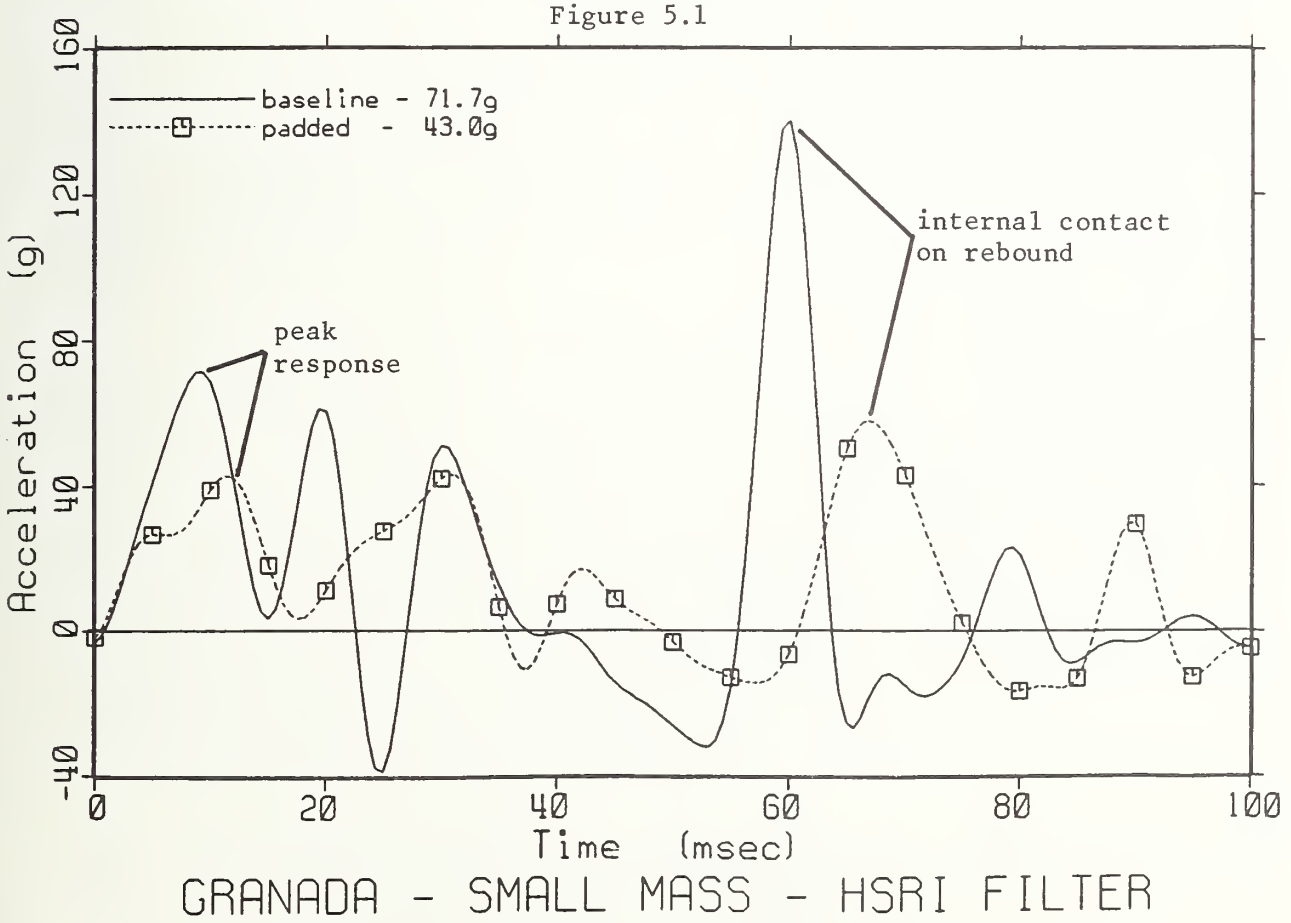
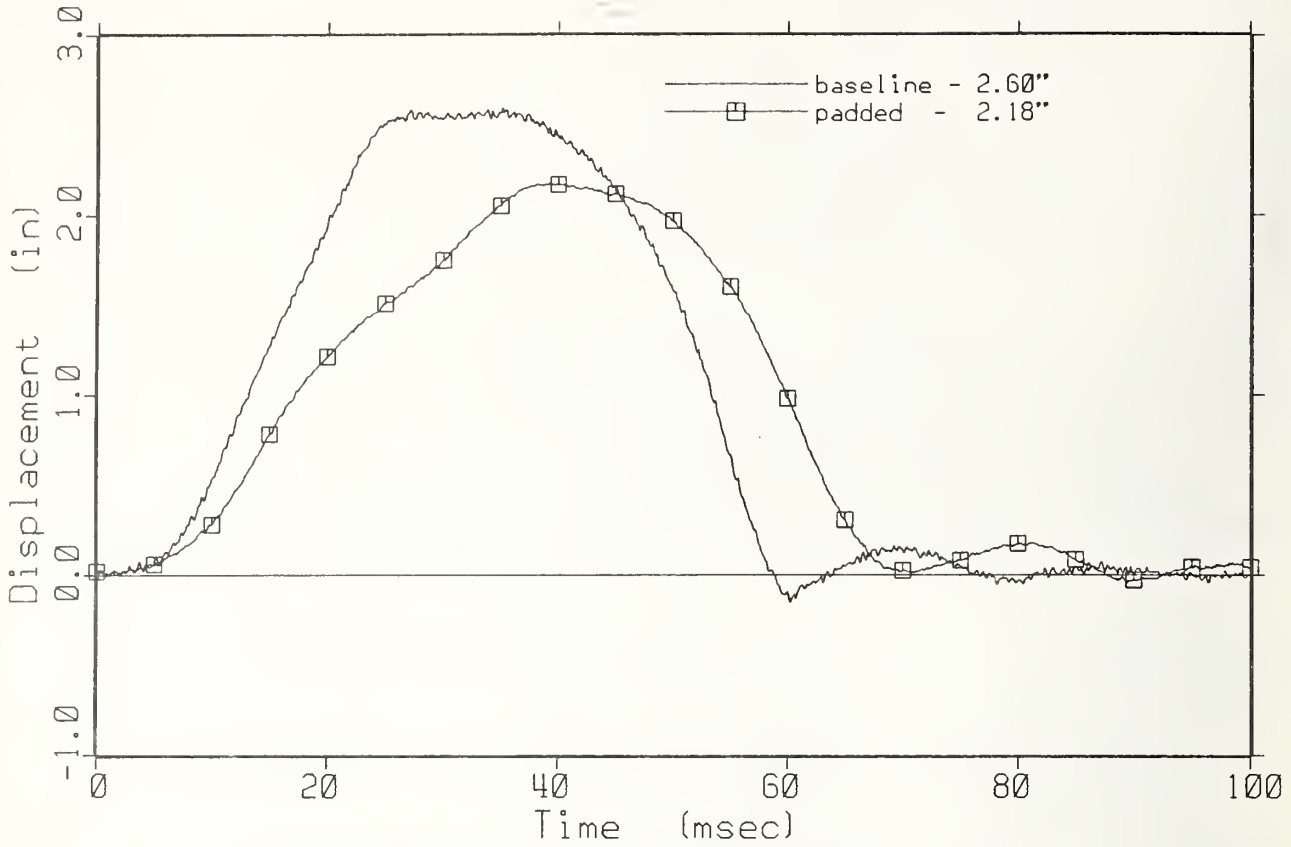
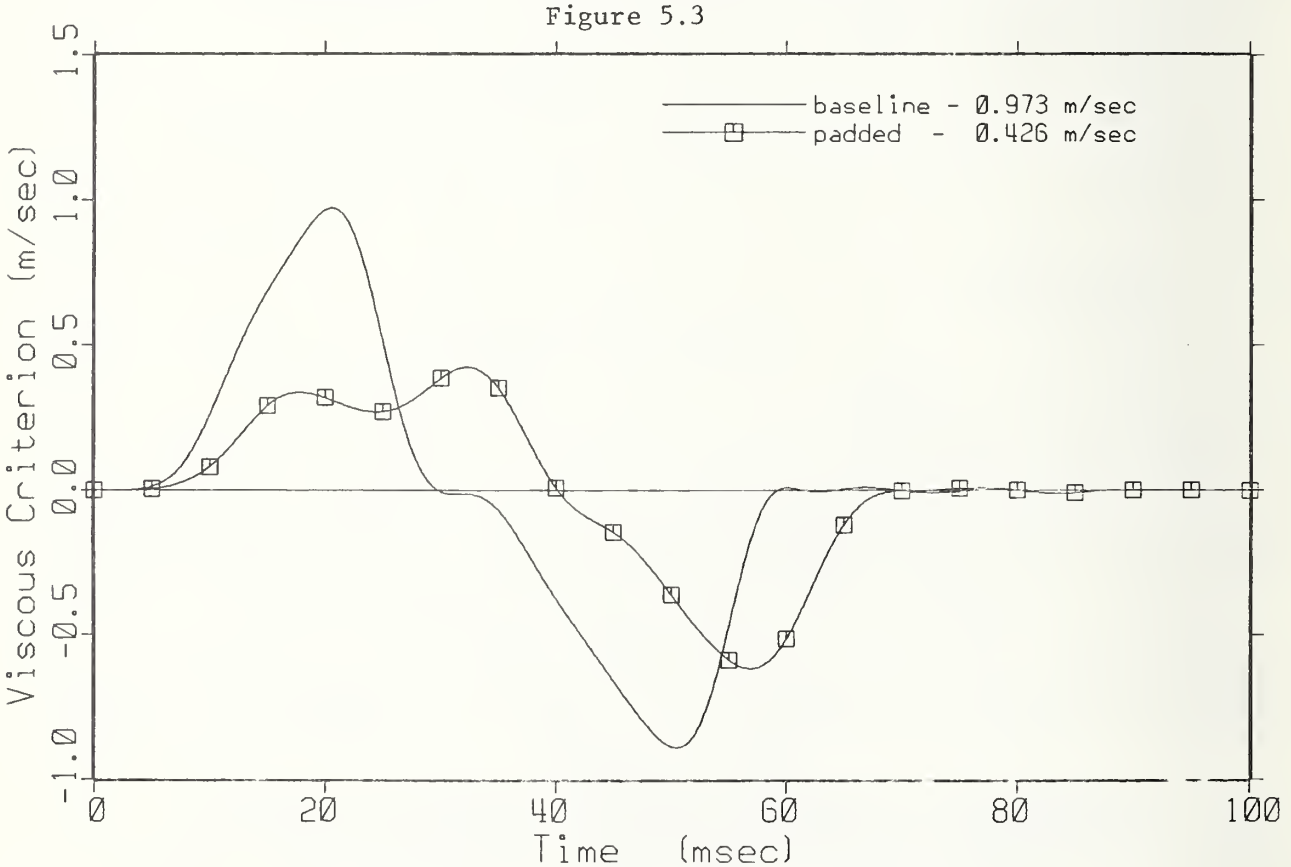


Figure 5.2



GRANADA - RELATIVE DEFLECTION

Figure 5.3



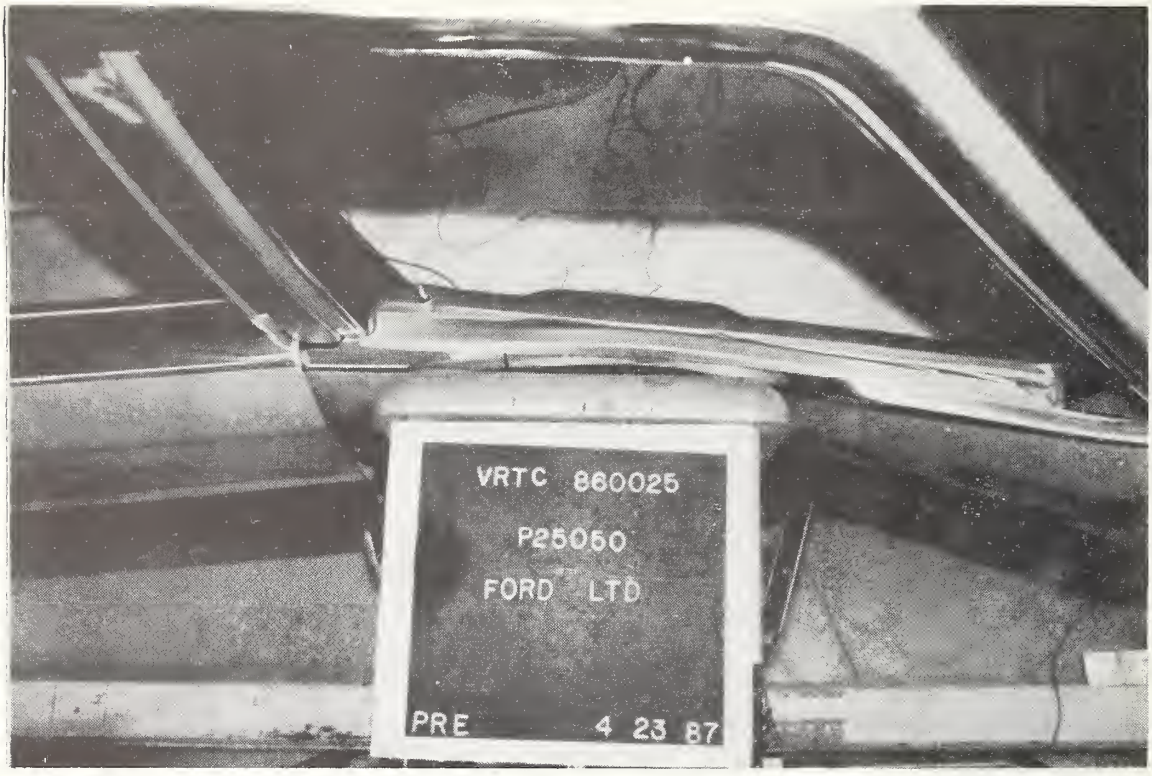
GRANADA - VISCOUS CRITERION

Figure 5.4

doors from the full-body (a) and fixtured door (b) baseline LTD tests are shown in Figure 5.5. Note that the full-body door followed the contour of the crush plate reasonably well while the fixtured door creased in the center, causing it to bend away from the crush plate. This left a large gap between the plate and the exterior surface of the door. As evidenced in the figure, the pre-crush locations for the fixtured door tests were determined differently from those of the full-body tests. One of the reasons for this was the proximity of the rigid fixturing. Details of this are contained in section 3.3.

Overlays of the force vs. exterior crush and inner panel displacement vs. exterior crush curves for the baseline LTD full-body and fixtured door tests are shown in Figures 5.6 and 5.7. The force curves are similar for the first 4 1/2" (115 mm) or so, but then they separate. As indicated in Figure 5.7, about 3 1/2" (90 mm) more exterior crush was required to produce inner panel displacement on the fixtured door than on the body mounted door. The main reason for these differences, as well as those of the crush patterns shown in Figure 5.5, was that the door fixture had a rigid "B-pillar" while that of the car body was not. The B-pillar of a car has a large effect on the side strength of a vehicle. Mounting a door in a rigid frame changed the crush characteristics significantly.

The results of the dynamic tests (listed in Tables 5.2 and 5.4) were also used to compare the two sub-system approaches. Three response measurements were used - TTI(age=0), peak relative deflection, and peak V*C. These are compared in Figures 5.8 through 5.10 for each door, with the full-body test results in increasing order. Linear correlations were done to compare the full-body test results with those of the fixtured door tests. The regressions produced coefficients of determination (r^2) for TTI(age=0), peak relative deflection, and peak V*C of 0.51, 0.14, and 0.00, respectively.



a. Full-Body Crush

b. Fixtured Door Crush

Figure 5.5 -- Baseline LTD Crush Comparison

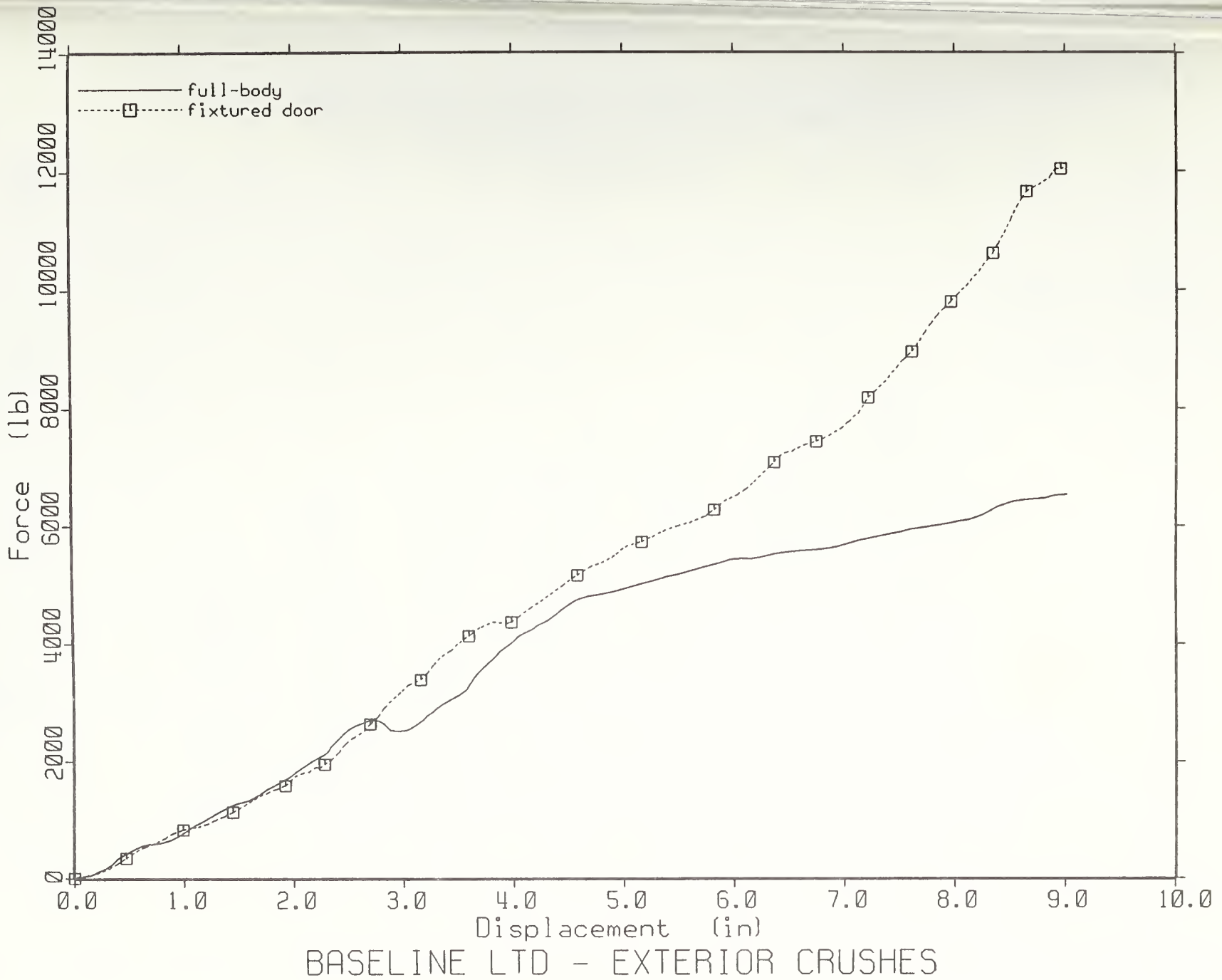

full-body
fixtured door
Force (lb)
0
2000
4000
6000
8000
10000
12000
14000
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Displacement (in)
BASELINE LTD - EXTERIOR CRUSHES

Figure 5.6

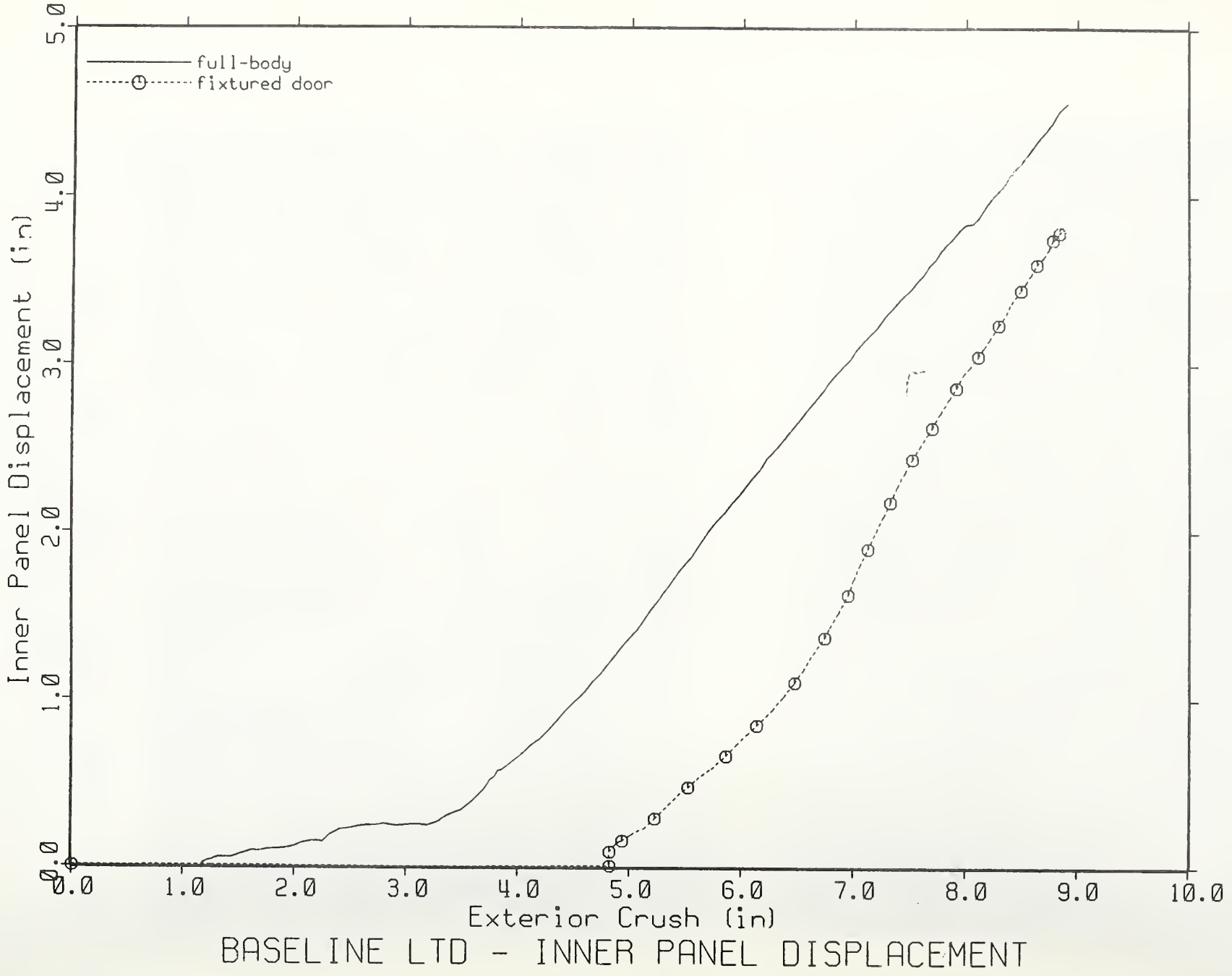

full-body
fixtured door
Inner Panel Displacement (in)
0.0
1.0
2.0
3.0
4.0
5.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Exterior Crush (in)
BASELINE LTD - INNER PANEL DISPLACEMENT

Figure 5.7

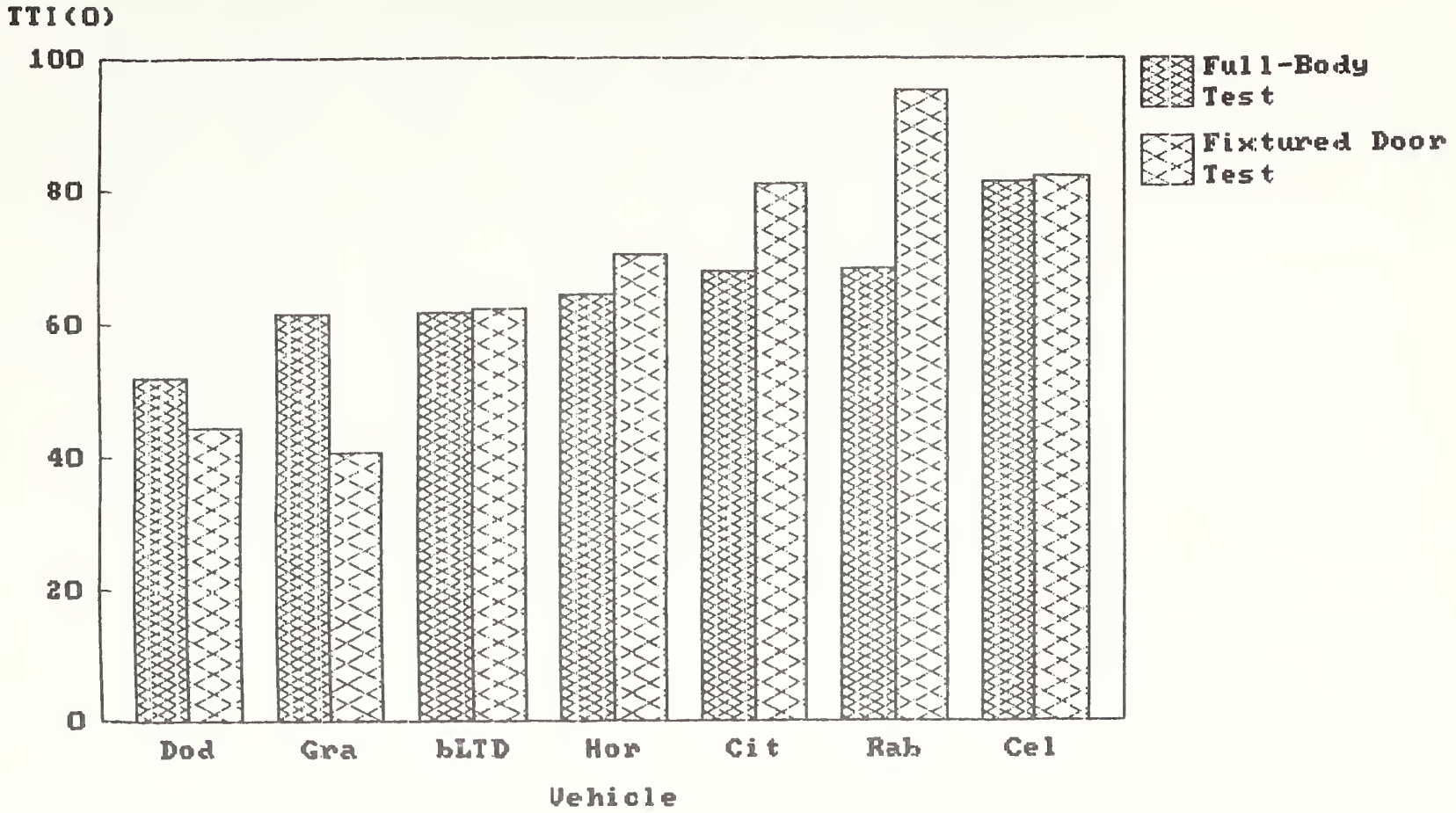

FULL-BODY/FIXTURED DOOR TEST COMPARISON
TTI(age=0)
TTI(0)
100
80
60
40
20
0
Dod
Gra
bLTD
Hor
Cit
Rab
Cel
Vehicle
Full-Body Test
Fixtured Door Test

Figure 5.8

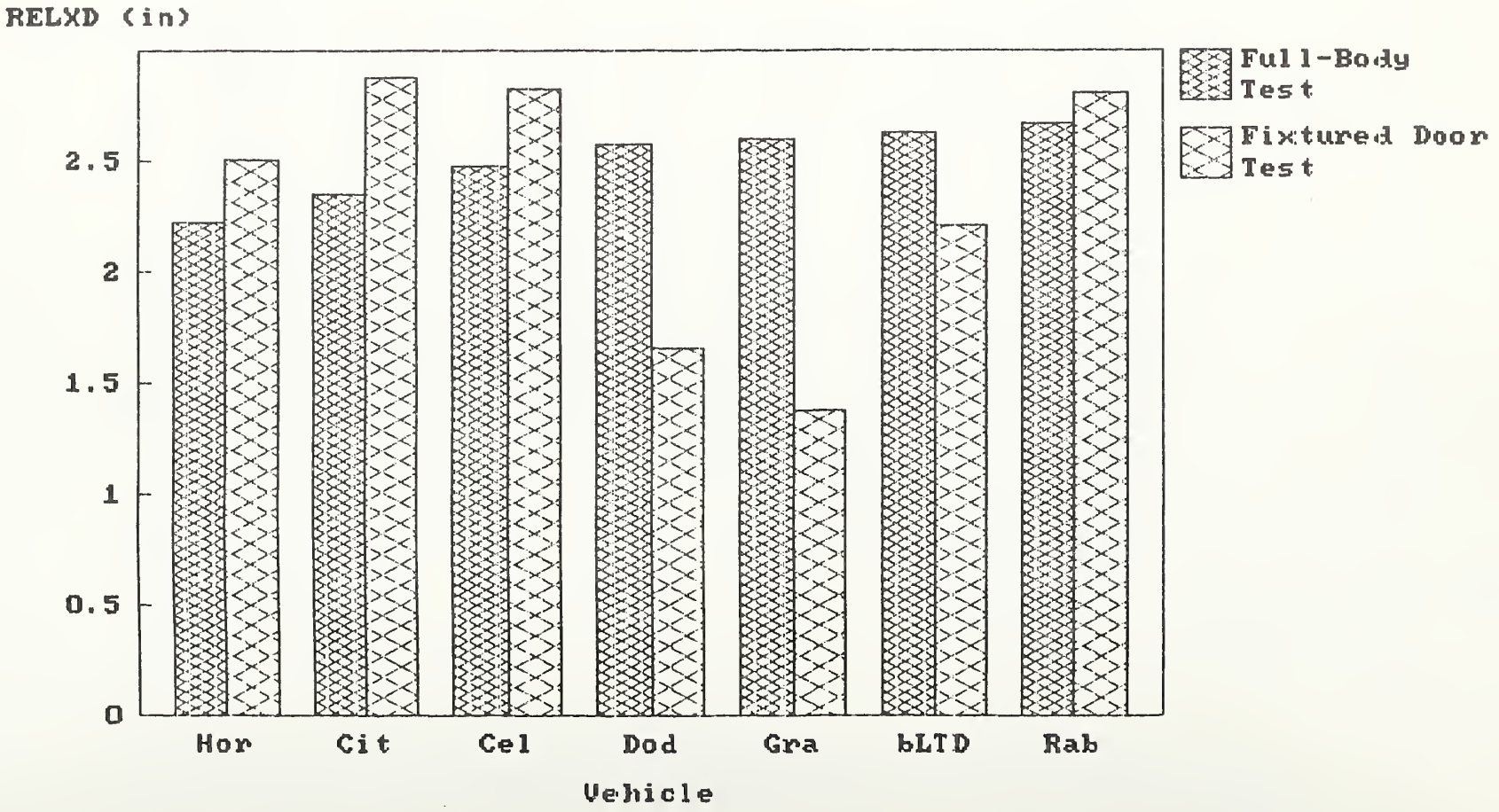

FULL-BODY/FIXTURED DOOR TEST COMPARISON
Peak Relative Deflection
RELXD (in)
2.5
2
1.5
1
0.5
0
Hor
Cit
Cel
Dod
Gra
bLTD
Rab
Vehicle
Full-Body Test
Fixtured Door Test

Figure 5.9

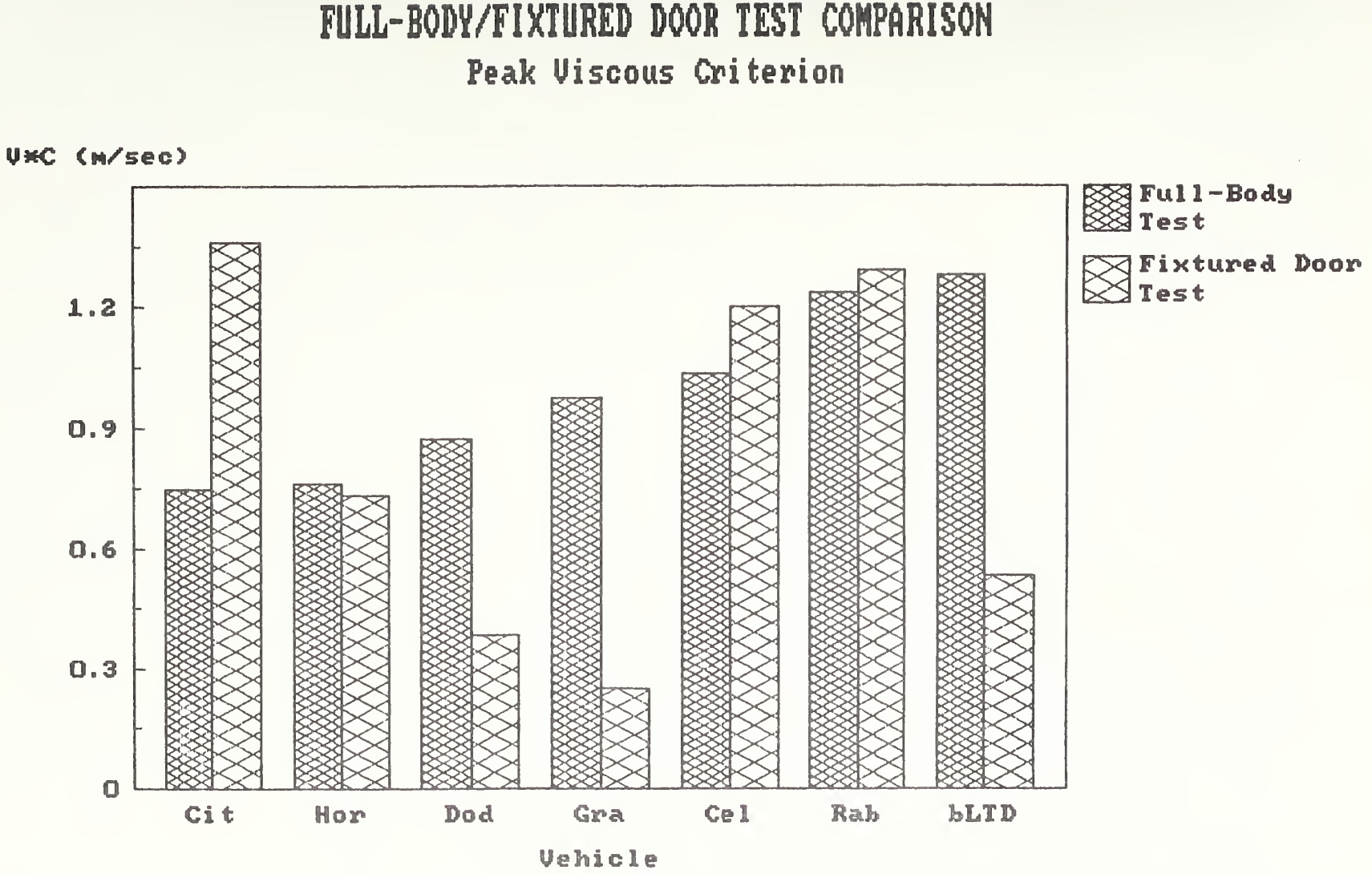

FULL-BODY/FIXTURED DOOR TEST COMPARISON
Peak Viscous Criterion
V*C (M/sec)
1.2
0.9
0.6
0.3
0
Cit
Hor
Dod
Gra
Cel
Rab
bLTD
Vehicle
Full-Body Test
Fixtured Door Test

Figure 5.10

The number of tests that produced essentially the same results ($|\Delta| \leq 10\%$), the number in which the full-body test produced higher results, and the number in which the fixtured door test produced higher results are summarized in Table 5.6. These figures and table indicate that one approach did not consistently give the same or higher results than the other, but that they varied considerably. Overall, there was a mild correlation of TTI values between the two approaches, and no significant correlation based upon deflection or V*C.

Table 5.6
FULL-BODY VS. FIXTURED DOOR TEST RESULTS
frequency summary

	TTI(0)	Relative Deflection	Peak V*C	average
same $\|\Delta\| \leq 10\%$	3	1	2	2
full-body higher	2	3	3	2 2/3
fixtured higher	2	3	2	2 1/3
total	7	7	7	7

5.2.3 Comparison of Full- and Sub-system Approaches

A second series of full-body tests were done using various impact speeds. These speeds were determined as described in section 3.4, and each was intended to be representative of the door-to-occupant contact velocity that occurred in the full-system crash test performed on that particular vehicle. The results of these tests (listed in Table 5.3) were compared to those from the crash tests. Comparisons were made based on TTI(age=0) only, since comparative relative deflections and V*C's were not available for the crash tests.

A comparison of the TTI(age=0) values for the crash tests (in increasing order) and for the second series of full-body sub-system tests is shown in Figure 5.11. Note that the baseline Granada test results from the first series of tests were used here rather than those from the second. The reason for this was that impact velocity found for this vehicle to simulate the crash test contact velocity was 17.9 mph (28.8 km/h), which was very close to the 18.0 mph (29.0 km/h) used in the first series of tests. It was felt that instead of repeating that condition, the second test would be done using a higher speed.

Two things stood out when the results were compared. First, the sub-system tests produced less severe impacts than the crash tests in every case, with an average decrease in TTI(age=0) of 34.4%. This may simply indicate that the impact velocities chosen for the sub-system tests were not high enough to produce similar injury levels as the crash tests. (Crash test data obtained since the completion of this study indicated that an impact velocity of 22 to 25 mph may have been more appropriate). Second, the injury levels predicted by the impactor showed little variation among the production vehicles. Excluding the modified LTD test, the average TTI(0) was 66.4, with a coefficient of variation of 7.9%. This compares to an coefficient of variation on the crash test TTI(age=0) values for the same eight vehicle models of 14.9% (see Table 5.4). A linear regression was done to compare the TTI(age=0) values of the sub-system tests with those of the crash tests. The resulting r^2 value was 0.02, indicating that no significant correlation existed. Overall, for the test procedures used in this study, the impactor and crash test results did not follow similar patterns and the results from one type of test could not be predicted by the results of the other.

Although comparisons with crash test results could not be made, two other response measurements were estimated from the impactor test results. As can be seen in Figure 5.12, the peak relative deflections from the second series of full-body tests, like the TTI(age=0) values, showed little variation among the production vehicles. Excluding the

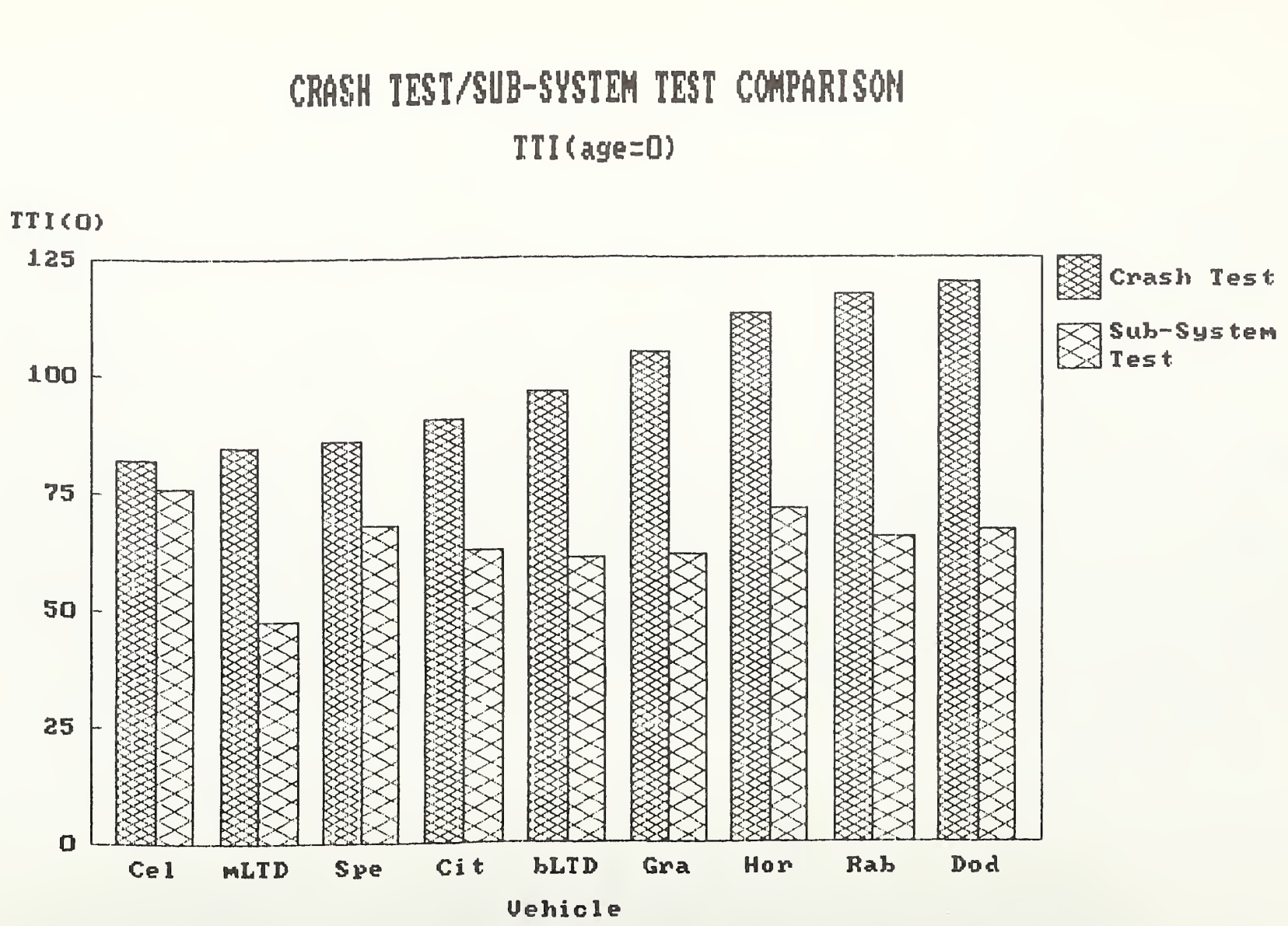

CRASH TEST/SUB-SYSTEM TEST COMPARISON
TTI(age=0)
TTI(0)
125
100
75
50
25
0
Cel
mLTD
Spe
Cit
bLTD
Gra
Hor
Rab
Dod
Vehicle
Crash Test
Sub-System Test

Figure 5.11

FULL-BODY SUB-SYSTEM TESTS: ADJUSTED VELOCITIES

Peak Relative Deflection

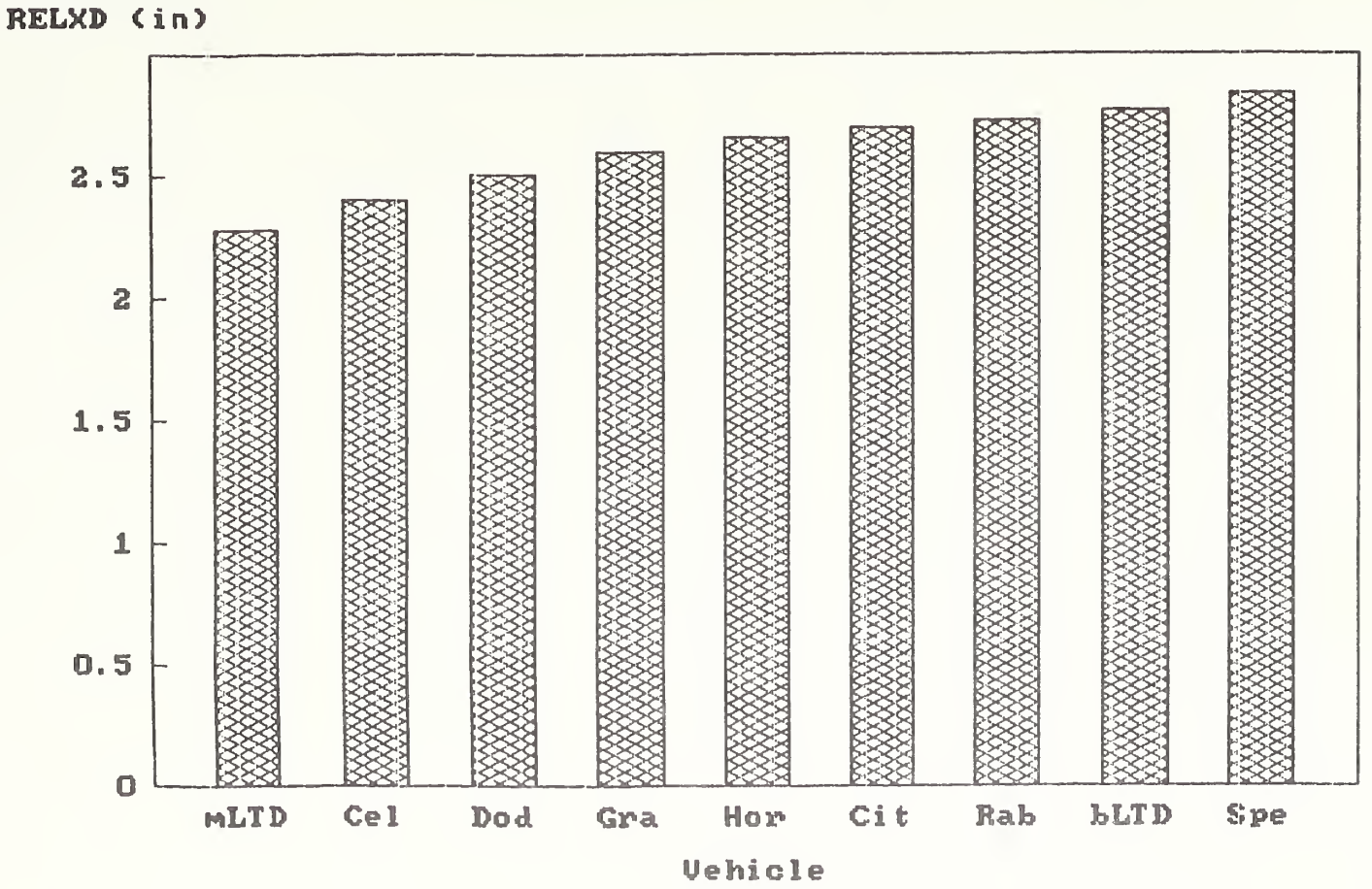


Figure 5.12

modified LTD, the average peak relative deflection was 2.65" (67.3 mm), with a coefficient of variation of 5.4%. The peak V*C values, on the otherhand, showed a higher level of variation (see Figure 5.13). Excluding the modified LTD, the average peak V*C was 1.064 m/sec, with a coefficient of variation of 19.5%.

It was also possible to distinguish between the baseline and structurally modified vehicles, using the impactor and this test procedure. The results of the LTD's done in the second series of full-body tests are contained in Table 5.7. As can be seen, all three response measurements decreased in the modified vehicle test. This was expected since the impact speed predicted from the study described in section 3.4 and used for testing for the modified LTD was 20% lower than that for the baseline vehicle (14.8 and 18.5 mph - 23.8 and 29.8 km/h, respectively). Note in Table 5.2, that when these two vehicles were tested at the same impact speed, the results were nearly identical.

Table 5.7
BASELINE/STRUCTURALLY MODIFIED LTD RESULTS

Ford LTD	TTI(0)	Peak Relative Deflection (in)	VC(max) (m/sec)
baseline	60.7	2.77	1.287
modified	47.4	2.28	0.613
decrease	21.9%	17.7%	52.4%

FULL-BODY SUB-SYSTEM TESTS: ADJUSTED VELOCITIES

Peak Viscous Criterion

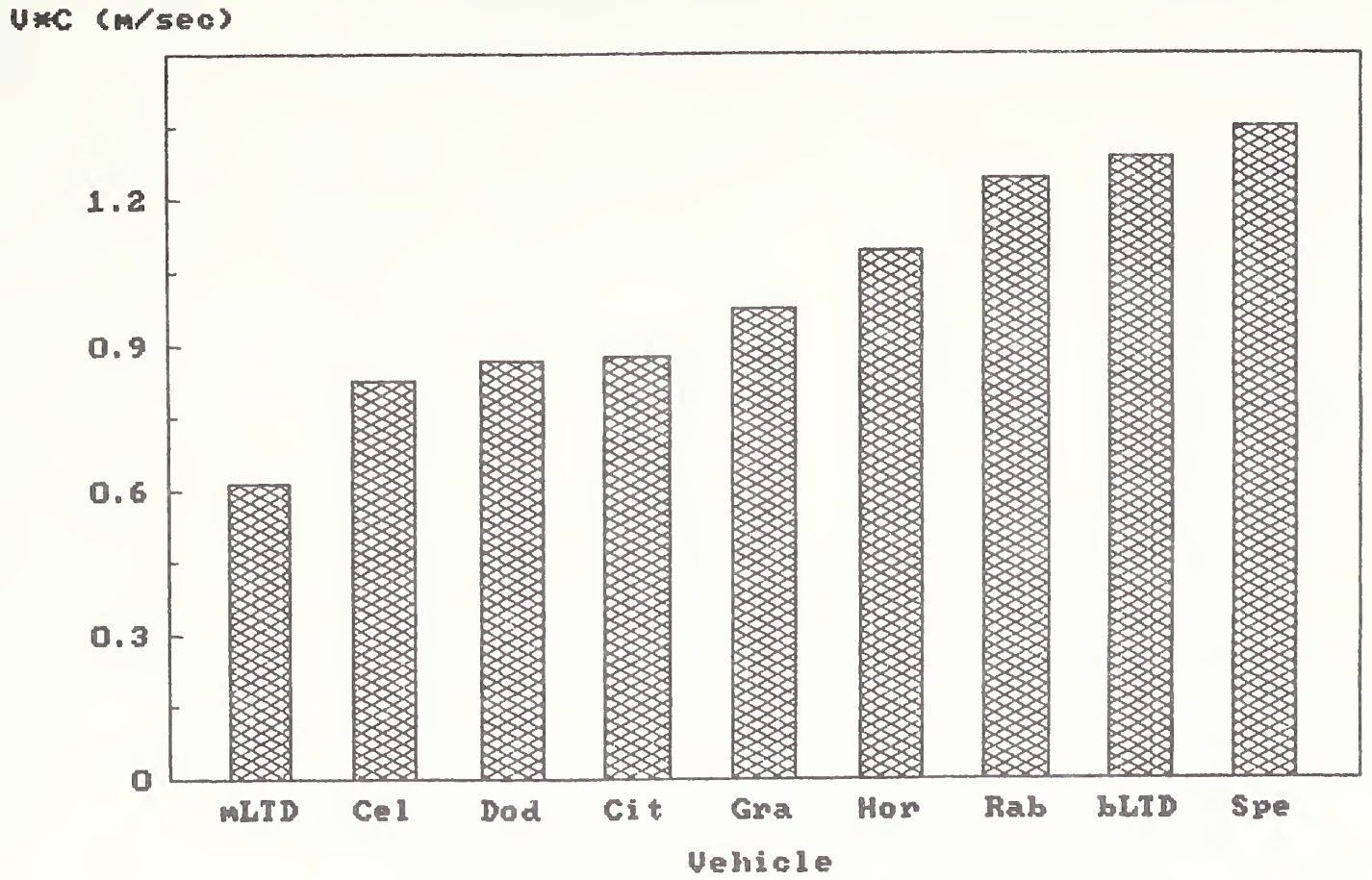


Figure 5.13

6.0 CONCLUSIONS

Based on the results and observations of this study, the following conclusions were made:

1. For the sub-system test procedures used in this study, the MVMA Thoracic Impactor and the full-system crash test results were essentially unrelated. The sub-system TTI(age=0) values were 34.4% lower, on average, than the crash test values. A linear regression comparing the two sets of values produced a coefficient of determination, r^2, of only 0.02.

2. The ability to show variation among the production vehicles tested using the thoracic impactor and the procedures of this study was dependent upon the response measurement considered. The coefficients of variation for the second series of full-body sub-system tests were as follows:

   TTI(age=0) - 7.9%
   peak realtive deflection - 5.4%
   peak Viscous Criterion (V*C) - 19.5%

   The coefficient of variation for the TTI(age=0) values from the crash tests on the same eight vehicle models was 14.9%

3. The 3" (76 mm) ArCel padding sample used on the Granada door resulted in substantial response reductions. With an impact speed of 18.0 mph (29.0 km/h), the padded test responses were reduced as follows:

   TTI(age=0) - 40%
   peak relative deflection - 16%
   peak Viscous Criterion - 56%

4. Using the thoracic impactor and the procedures of this study, it was possible to distinguish between baseline and structurally

modified vehicles only if an impact velocity adjustment procedure was applied. When both were tested at a nominal speed of 18 mph (29 km/h), the structurally modified vehicle produced the following response changes:

TTI(age=0) - 3.1% increase
peak relative deflection - 1.5% increase
peak Viscous Criterion - 2.2% increase

Using the adjusted impact speeds of 18.4 and 14.8 mph (29.6 and 23.8 km/h) for the baseline and modified vehicle tests, respectively, the modified vehicle responses were reduced as follows:

TTI(age=0) - 21.9%
peak relative deflection - 17.7%
peak Viscous Criterion - 52.4%

5. Using a nominal impact speed of 18 mph (29 km/h) for all tests, a slight correlation was found between the TTI results of the full-body sub-system tests and the fixtured door sub-system tests. No significant correlation was found using other response measurements. Linear regressions performed to compare the two sub-system test approaches produced the following coefficients of determination, r^2:

TTI(age=0) - 0.51
peak relative deflection - 0.14
peak Viscous Criterion - 0.00

6. The peak relative deflections measured in this study using the thoracic impactor may not be reliable for measuring injury potential. Many of the traces flattened near the peak, possibly due to internal friction. Since peak accelerations and peak V*C occur prior to this flattening, and since the exact cause of this occurrence was not determined, it is impossible to determine what,

if any, effect it would have on acceleration and velocity based responses.

7. The thoracic impactor did not meet the calibration corridors as well as desired, but its calibration performance was judged to be acceptable. The original 1 meter drop speed calibration test done on the impactor produced a force-time history that stayed within the corridor during most of the loading phase, but peaked about 350 lb (159 kg) above the corridor. Peak relative deflection for this test was 1.40" (35.6 mm), which was 0.10" (2.5 mm) above the corridor. The original 2 meter drop speed calibration test produced a force-time history that matched the corridor very well. Peak relative deflection for this test was 2.43" (61.7 mm), which was 0.58" (14.7 mm) above the corridor.

8. A slow-rate crush test on the thoracic impactor produced a three part force vs. deflection curve. Force rose linearly for about 1.4" (36 mm), dropped off due to bulging/buckling of the Urethane main spring, and then increased sharply, as the conical secondary spring began to bottom out.

9. The durability of the conical secondary spring used in the thoracic impactor was not good. During the course of testing, two were torn and replaced, one was damaged. It was determined that deterioration occurred gradually from the inside surface.

10. The response of the thoracic impactor was somewhat sensitive to the condition of the conical secondary spring. Calibration tests done following the replacement of the torn conical spring with a new one produced different results. The 1 meter drop speed test showed very little change from the corresponding original test, with a peak relative deflection of 1.37" (34.8 mm). The 2 meter drop speed calibration test produced a different force-time history than that of the corresponding original test, peaking about 300 lb (136 kg) higher than the first test. The peak relative deflection was 2.39" (60.7 mm).

11. When the Urethane main spring was replaced with the Ethafoam 600 spring and the conical secondary spring was removed, the performance of the thoracic impactor against the calibration corridors improved. The 1 meter drop speed calibration test produced a force-time history that was within the corridor throughout the entire event. The peak relative deflection measured from this test was 1.24" (31.5 mm), which was also within the corridor. The 2 meter drop speed calibration produced a force-time history that dipped low during the loading phase and then peaked about 50 lb (23 kg) high. The peak relative deflection of 2.15" (54.6 mm) was 0.30" (7.6 mm) above the corridor.

12. A slow-rate crush test on the thoracic impactor with the Ethafoam 600 spring produced a continuously increasing force vs. deflection curve. This spring crushed in a uniform manner, without the occurrence of buckling.

13. Testing with the thoracic impactor using the Ethafoam 600 spring indicated that up to an hour was required for this spring to fully recover. The time varied based on the impact speed.

14. Throughout the testing of this study, the overall mechanical performance of the thoracic impactor was good. It was durable and the impact velocity was repeatable. There were three concerns on the mechanical aspects of the device, though. These were as follows:

    a. durability of the conical secondary spring
    b. 'ringing' on the large mass, and
    c. flattened relative deflection at peak

15. The operating program did a good job of coordinating the functions of the control and data acquisition systems and had good utility.

16. The control system was organized in a straight forward manner, but problems were frequently encountered. These often made it necessary to re-boot the entire system. None of the problems allowed a

premature fire of the impactor, though, indicating that the built in safeties worked well.

17. No problems were encountered with the operation of the data acquisition system. Increasing the sampling rate to at least 8000 Hz from the current 4400 Hz would make it compatible with the Class 1000 filter applied to the data.

7.0 REFERENCES

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3. Leonard R. Kamholz, Patrick M. Miller; "Sub-System Testing and Evaluation of MVMA Thorax Impactor"; Final Report for MGA Agreement No. MGA 8626-C6137C, MGA File No. C86R-06; November 1986.

4. Tarriere, C., et al.; "Synthesis of Human Tolerances Obtained from Lateral Impact Simulations;" Seventh International Technical Conference on Experimental Safety Vehicles; June, 1979.

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6. Hamilton, Michael N.; "Experimental Study of Thoracic Injury in Child Pedestrians;" presented at the Eleventh International Conference on Experimental Safety Vehicles; May 1987.

7. Lau, Ian V. and Viano, David C.; "The Viscous Criterion-Bases and Applications of an Injury Severity Index for Soft Tissues;" paper number 861882 presented at the Thirtieth Stapp Car Crash Conference; October, 1986.

APPENDIX A

VRTC Test Procedure Summary

This Appendix summarizes the information specified in Chapter 3 of this report. This includes listing the vehicles tested as well as outlining the tests and test conditions done on these vehicles.

A.1 Vehicles

Nine vehicles were selected for sub-system testing. For each of these models, 30/15 mph, 90°, MDB side impact crash test data has been collected. The vehicles are as follows:

4-door Chevrolet Celebrity
4-door Chevrolet Citation
2-door Dodge 400
2-door Ford Granada
4-door Plymouth Horizon
4-door baseline Ford LTD
4-door structurally modified Ford LTD
2-door Volkswagen Rabbit
2-door Chevrolet Spectrum

A.2 Test Series

Three series of tests were performed. The first two involved the use of the entire body of the car, with series 1 tests done on the left side and series 2 tests done on the right side of each vehicle. The third series of tests were performed on the doors of these cars mounted in a frame outside the vehicle. A pre-crush was performed prior to the dynamic test on each car/door. The specific conditions of each follow.

Test Series No. 1

The full body of each car was secured, pre-crushed, and impacted on its left side under the following conditions:

impact location - The location of dummy contact on the door was determined from crash test photographs and/or movies for each vehicle. This location was duplicated in the unpadded tests for this series (see Table 3.1). Padded tests were done on the same doors 5" (127 mm) forward of the unpadded impact locations for several of the cars. These tests were not continued due to excessive door damage from the unpadded tests (see section 3.2). For one car then, the door was replaced, padding was added to the door, and a padded test was conducted at the same impact location that was used for the unpadded test on that vehicle. For all tests, the impactor was vertically positioned to strike just below the window opening of the door.

pre-crush - Each door/side structure was pre-crushed using the VRTC crushing apparatus. The crush plate was centered between the unpadded and original padded impact locations, that is, 2.5" (63.5 mm) forward of the impact location determined from crash test photography (see Table 3.1). The crush plate was vertically postioned such that its lower edge was 15.7" (400 mm) above the ground reference plane for each car (see Table 3.2). The amount of pre-crush was 9.1" (230 mm) of exterior door crush after initial contact of the plate with the exterior surface.

impact velocity - The impact velocity for each of these tests was 18 mph (29 km/h). This was determined as the average door velocity in the crash tests of these vehicles.

door mitigation - Each car was tested in the unpadded condition. Several of the doors were re-tested, 5" forward, using padding. For one of the cars, the door was replaced and tested, also with padding. In each padded case, the interior trim panel was removed and an 8" by 12" by 3" thick (203.2 x 304.8 x 76.2 mm) piece of ArCel padding was attached to the door. The padding

was softened by drilling nine 7/8" (22.2 mm) vertical holes through it.

In summary, this series of tests consisted of an unpadded test for each car. For some of the vehicles, a padded test was also performed. All tests were done at 18 mph (29 km/h) at the pre-determined occupant impact location. Exterior crush data were collected for all vehicles.

The objectives of this series of tests were as follows:

1. To determine the ability of the MVMA device to distinguish between unpadded and padded doors.
2. To determine the ability of the MVMA device to distinguish between different vehicles when tested at the same impact velocity.
3. To obtain exterior crush data for each vehicle, for use in developing a velocity adjustment procedure based upon side structural strength.

Test Series No. 2

The full body of each car was secured, pre-crushed, and impacted on its right side under the following conditions:

impact location - The impact location for each vehicle was identical to that used in the unpadded test in the first series (see Table 3.1).

pre-crush - The pre-crush location and extent for each vehicle was identical to that used in the first series (see Tables 3.1 and 3.2).

impact velocity - The impact speed was determined separately for each vehicle based on its side structural stiffness measured during the pre-crush in the first series of tests (see Table 3.7).

door mitigation - Each vehicle was tested in the unpadded configuration only.

In summary, this series of tests consisted of an unpadded test for each car. Impact occurred at the pre-determined location for each car at an impact velocity determined from the side structural stiffness measured during the pre-crush in the first series of tests. Exterior crush data were taken for all tests of this series.

The objectives of this test series were as follows:

1. To allow a comparison between the results of the MVMA impactor tests to those of the crash tests for each vehicle.
2. To examine the ability of the sub-system approach to distinguish between good and poor door/side structure designs.

Door-in-Frame Tests

For this series of tests, each door was removed from the vehicle and mounted in a rigid frame. Each door was mounted, pre-crushed, and impacted under the following conditions:

impact location - The impactor was positioned such that impact occurred just below the window opening of the door, horizontally centered on the crush plate.

pre-crush - The crush plate was positioned such that its vertical centerline passed through the mid-seat H-point location for that vehicle. If necessary, the crush plate was moved to maintain a minimum of 3" (75 mm) between the crush plate and the door opening (see Table 3.3). The vertical position of the crush plate was identical to that of the first two test series (see Table 3.2). Also as before, the extent of pre-crush was 9.1" (230 mm) of exterior movement.

impact velocity - All tests were done at 18 mph (29 km/h).

door mitigation - Each door was tested in the unpadded configuration only.

In summary, this series consisted of a frame-mounted, unpadded door test for each car. Each door was impacted at the same speed used in the first series of full-body tests, 18 mph (29 km/h). The crush

plate was aligned such that its centerline passed through the mid-seat H-point location, unless altered to maintain a 3" (75 mm) gap between the plate and the door opening. Impacts were horizontally centered on the crush plate and exterior crush data were taken for each door.

The objective of this test series was to compare the results of the full-body and frame-mounted door sub-system test approaches.

APPENDIX B

SAS Results For
Contact Velocity Regression

```
  T CRUSHCOR.SAS
DATA CRUSH;
INPUT STIFF FORCE ENERGY RIBV SPINEV DR02FV DRMAXV DR02NV;
 CARDS;
 920  7580 3252 22.4 25.7 18.2 21.4 19.5
 904  7744 3624 24.7 27.1 17.4 20.7 18.3
 777  6793 3228 25.3 26.1 18.0 18.1 21.2
 947  7606 3245 23.6 26.7 21.9 26.1 18.2
 690  6962 3516 24.6 27.1 14.1 18.4 15.8
 774  6548 2911 22.5 26.0 15.1 19.3 16.2
1770 13382 5308 19.5 21.6 14.3 20.9 15.0
 633  5768 2956 24.8 29.6 18.4 20.6 15.2
 666  6119 2903 25.5 27.2 17.5 18.6 24.0
;
PROC RSQUARE;
MODEL STIFF=RIBV SPINEV DR02FV DRMAXV DR02NV/STOP=2;
MODEL FORCE=RIBV SPINEV DR02FV DRMAXV DR02NV/STOP=2;
MODEL ENERGY=RIBV SPINEV DR02FV DRMAXV DR02NV/STOP=2;
$
$
$
$ T CRUSHCOR.LIS
```

N=9 REGRESSION MODELS FOR DEPENDENT VARIABLE: STIFF MODEL: MODEL1

NUMBER IN MODEL	R-SQUARE	VARIABLES IN MODEL
1	0.07500821	DR02FV
1	0.08186805	DRMAXV
1	0.12168658	DR02NV
1	0.75469026	RIBV
1	0.81145854	SPINEV
2	0.14454361	DR02FV DR02NV
2	0.17191170	DRMAXV DR02NV
2	0.50185182	DR02FV DRMAXV
2	0.75605788	RIBV DRMAXV
2	0.75633702	RIBV DR02FV
2	0.76805791	RIBV DR02NV
2	0.82440571	SPINEV DR02FV
2	0.85398111	RIBV SPINEV
2	0.85756885	SPINEV DR02NV
2	0.86805681	SPINEV DRMAXV

N=9 REGRESSION MODELS FOR DEPENDENT VARIABLE: FORCE MODEL: MODEL2

NUMBER IN MODEL	R-SQUARE	VARIABLES IN MODEL
1	0.04638011	DRMAXV
1	0.12759038	DR02FV
1	0.13772701	DR02NV
1	0.70951310	RIBV
1	0.80807493	SPINEV
2	0.15955460	DRMAXV DR02NV
2	0.19163175	DR02FV DR02NV
2	0.53052310	DR02FV DRMAXV
2	0.71035239	RIBV DRMAXV
2	0.71297509	RIBV DR02FV
2	0.71494902	RIBV DR02NV
2	0.80852290	SPINEV DR02FV
2	0.83381065	RIBV SPINEV
2	0.83600965	SPINEV DRMAXV
2	0.86451063	SPINEV DR02NV

N=9 REGRESSION MODELS FOR DEPENDENT VARIABLE: ENERGY MODEL: MODEL3

NUMBER IN MODEL	R-SQUARE	VARIABLES IN MODEL
1	0.01031646	DRMAXV
1	0.17830831	DR02NV
1	0.20021401	DR02FV
1	0.55319506	RIBV
1	0.68284100	SPINEV
2	0.17879172	DRMAXV DR02NV
2	0.27355860	DR02FV DR02NV
2	0.51777018	DR02FV DRMAXV
2	0.55524448	RIBV DR02NV
2	0.56714518	RIBV DRMAXV
2	0.59060866	RIBV DR02FV
2	0.68610141	SPINEV DRMAXV
2	0.69114796	RIBV SPINEV
2	0.69531653	SPINEV DR02FV
2	0.77310821	SPINEV DR02NV

```
  T CRUSHCOR.SAS;13
DATA CRUSH;
INPUT STIFF FORCE ENERGY RIBV SPINEV DRO2FV DRMAXV DRO2NV;
 CARDS;
 920  7580 3252 22.4 25.7 18.2 21.4 19.5
 904  7744 3624 24.7 27.1 17.4 20.7 18.3
 777  6793 3228 25.3 26.1 18.0 18.1 21.2
 947  7606 3245 23.6 26.7 21.9 26.1 18.2
 690  6962 3516 24.6 27.1 14.1 18.4 15.8
 774  6548 2911 22.5 26.0 15.1 19.3 16.2
1770 13382 5308 19.5 21.6 14.3 20.9 15.0
 633  5768 2956 24.8 29.6 18.4 20.6 15.2
 666  6119 2903 25.5 27.2 17.5 18.6 24.0
;
PROC STEPWISE;
MODEL STIFF=RIBV SPINEV DRO2FV DRMAXV DRO2NV/MINR STOP=2;
MODEL FORCE=RIBV SPINEV DRO2FV DRMAXV DRO2NV/MINR STOP=2;
MODEL ENERGY=RIBV SPINEV DRO2FV DRMAXV DRO2NV/MINR STOP=2;
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MINIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE STIFF

STEP 1 VARIABLE DR02FV ENTERED R SQUARE = 0.07500821 C(P) = 22.95819631

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	1	72055.50179512	72055.50179512	0.57	0.4758
ERROR	7	888579.38709377	126939.91244197		
TOTAL	8	960634.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	1566.62044883				
DR02FV	-38.85464196	51.57134226	72055.50179512	0.57	0.4758

BOUNDS ON CONDITION NUMBER: 1, 1

STEP 1 DR02FV REPLACED BY DRMAXV R SQUARE = 0.08186805 C(P) = 22.75085528

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	1	78645.30325934	78645.30325934	0.62	0.4554
ERROR	7	881989.58562955	125998.51223279		
TOTAL	8	960634.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	66.26814403				
DRMAXV	40.65500654	51.45888219	78645.30325934	0.62	0.4554

BOUNDS ON CONDITION NUMBER: 1, 1

STEP 1 DRMAXV REPLACED BY DR02NV R SQUARE = 0.12168658 C(P) = 21.54732638

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	1	116896.37511407	116896.37511407	0.97	0.3575
ERROR	7	843738.51377481	120534.07339640		
TOTAL	8	960634.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	1622.81251705				
DR02NV	-39.92847401	40.54498157	116896.37511407	0.97	0.3575

BOUNDS ON CONDITION NUMBER: 1, 1

MINIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE STIFF

STEP 1 DR02NV REPLACED BY RIBV R SQUARE = 0.75469026 C(P) = 2.41457148

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	1	724981.79769298	724981.79769298	21.54	0.0024
ERROR	7	235653.09119591	33664.72731370		
TOTAL	8	960634.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	4601.12417368				
RIBV	-156.54822716	33.73433496	724981.79769298	21.54	0.0024

BOUNDS ON CONDITION NUMBER: 1, 1

STEP 1 RIBV REPLACED BY SPINEV R SQUARE = 0.81145854 C(P) = 0.69873087

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	1	779515.37989474	779515.37989474	30.13	0.0009
ERROR	7	181119.50899415	25874.21557059		
TOTAL	8	960634.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	4790.61424748				
SPINEV	-147.76266650	26.92067665	779515.37989474	30.13	0.0009

BOUNDS ON CONDITION NUMBER: 1, 1

THE ABOVE MODEL IS THE BEST 1 VARIABLE MODEL FOUND.

STEP 2 VARIABLE DR02FV ENTERED R SQUARE = 0.82440571 C(P) = 2.30739811

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	2	791952.88568630	395976.44284315	14.08	0.0054
ERROR	6	168682.00320259	28113.66720043		
TOTAL	8	960634.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	4711.39968682				
SPINEV	-156.36918651	30.90114905	719897.38389118	25.61	0.0023
DR02FV	17.77622299	26.72585398	12437.50579156	0.44	0.5307

BOUNDS ON CONDITION NUMBER: 1.212626, 4.850505

MINIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE STIFF

STEP 2 DR02FV REPLACED BY RIBV R SQUARE = 0.85398111 C(P) = 1.41347147

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	2	820364.04555207	410182.02277603	17.55	0.0031
ERROR	6	140270.84333682	23378.47388947		
TOTAL	8	960634.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	5030.87220973				
RIBV	-68.54097553	51.85246690	40848.66565733	1.75	0.2344
SPINEV	-95.33730998	47.19947805	95382.24785909	4.08	0.0899

BOUNDS ON CONDITION NUMBER: 3.40215, 13.6086

STEP 2 RIBV REPLACED BY DR02NV R SQUARE = 0.85756885 C(P) = 1.30503066

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	2	823810.55787221	411905.27893610	18.06	0.0029
ERROR	6	136824.33101668	22804.05516945		
TOTAL	8	960634.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	5099.73056875				
SPINEV	-142.35944148	25.56871895	706914.18275814	31.00	0.0014
DR02NV	-24.86628852	17.84180483	44295.17797747	1.94	0.2128

BOUNDS ON CONDITION NUMBER: 1.023531, 4.094125

STEP 2 DR02NV REPLACED BY DRMAXV R SQUARE = 0.86805681 C(P) = 0.98802850

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	2	833885.65645528	416942.82822764	19.74	0.0023
ERROR	6	126749.23243360	21124.87207227		
TOTAL	8	960634.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	4042.63276833				
SPINEV	-145.65557789	24.36024047	755240.35319595	35.75	0.0010
DRMAXV	33.85248562	21.10118451	54370.27656054	2.57	0.1598

BOUNDS ON CONDITION NUMBER: 1.002915, 4.011662

THE ABOVE MODEL IS THE BEST 2 VARIABLE MODEL FOUND.

MINIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE FORCE

STEP 1 VARIABLE DRMAXV ENTERED R SQUARE = 0.04638011 C(P) = 20.53818095

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	1	1909289.16609844	1909289.16609844	0.34	0.5779
ERROR	7	39256832.83390156	5608118.97627165		
TOTAL	8	41166122.00000000			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	3513.77851205				
DRMAXV	200.31501027	343.30983796	1909289.16609844	0.34	0.5779

BOUNDS ON CONDITION NUMBER: 1, 1

STEP 1 DRMAXV REPLACED BY DR02FV R SQUARE = 0.12759038 C(P) = 18.36334930

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	1	5252401.29455720	5252401.29455720	1.02	0.3453
ERROR	7	35913720.70544280	5130531.52934897		
TOTAL	8	41166122.00000000			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	13320.82174783				
DR02FV	-331.73270323	327.86157309	5252401.29455720	1.02	0.3453

BOUNDS ON CONDITION NUMBER: 1, 1

STEP 1 DR02FV REPLACED BY DR02NV R SQUARE = 0.13772701 C(P) = 18.09188792

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	1	5669686.85534171	5669686.85534171	1.12	0.3255
ERROR	7	35496435.14465829	5070919.30637976		
TOTAL	8	41166122.00000000			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	12659.93689953				
DR02NV	-278.07485983	262.98170721	5669686.85534171	1.12	0.3255

BOUNDS ON CONDITION NUMBER: 1, 1

MINIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE FORCE

STEP 1 DR02NV REPLACED BY RIBV R SQUARE = 0.70951310 C(P) = 2.77931240

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	1	29207902.77779447	29207902.77779447	17.10	0.0044
ERROR	7	11958219.22220553	1708317.03174365		
TOTAL	8	41166122.00000000			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	31116.74932392				
RIBV	-993.65309495	240.30833688	29207902.77779447	17.10	0.0044

BOUNDS ON CONDITION NUMBER: 1, 1

STEP 1 RIBV REPLACED BY SPINEV R SQUARE = 0.80807493 C(P) = 0.13980181

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	1	33265311.01982462	33265311.01982462	29.47	0.0010
ERROR	7	7900810.98017538	1128687.28288220		
TOTAL	8	41166122.00000000			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	33040.79780281				
SPINEV	-965.26857961	177.80304385	33265311.01982462	29.47	0.0010

BOUNDS ON CONDITION NUMBER: 1, 1

THE ABOVE MODEL IS THE BEST 1 VARIABLE MODEL FOUND.

STEP 2 VARIABLE DR02FV ENTERED R SQUARE = 0.80852290 C(P) = 2.12780490

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	2	33283752.45089484	16641876.22544742	12.67	0.0070
ERROR	6	7882369.54910516	1313728.25818419		
TOTAL	8	41166122.00000000			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	32944.34037432				
SPINEV	-975.74850630	211.23634774	28031351.15633765	21.34	0.0036
DR02FV	21.64562605	182.69455852	18441.43107022	0.01	0.9096

BOUNDS ON CONDITION NUMBER: 1.212626, 4.850505

MINIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE FORCE

STEP 2 DR02FV REPLACED BY RIBV R SQUARE = 0.83381065 C(P) = 1.45059261

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	2	34324751.02174020	17162375.51087010	15.05	0.0046
ERROR	6	6841370.97825980	1140228.49637663		
TOTAL	8	41166122.00000000			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	34264.36277421				
RIBV	-349.05955241	362.12398369	1059440.00191557	0.93	0.3723
SPINEV	-698.28125795	329.62873404	5116848.24394573	4.49	0.0785

BOUNDS ON CONDITION NUMBER: 3.40215, 13.6086

STEP 2 RIBV REPLACED BY DRMAXV R SQUARE = 0.83600965 C(P) = 1.39170295

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	2	34415275.14516652	17207637.57258326	15.29	0.0044
ERROR	6	6750846.85483348	1125141.14247225		
TOTAL	8	41166122.00000000			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	29600.84709533				
SPINEV	-955.57812449	177.78209927	32505985.97906807	28.89	0.0017
DRMAXV	155.68685202	153.99736650	1149964.12534190	1.02	0.3510

BOUNDS ON CONDITION NUMBER: 1.002915, 4.011662

STEP 2 DRMAXV REPLACED BY DR02NV R SQUARE = 0.86451063 C(P) = 0.62843948

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	2	35588550.03031661	17794275.01515831	19.14	0.0025
ERROR	6	5577571.96968339	929595.32828056		
TOTAL	8	41166122.00000000			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	35279.47077793				
SPINEV	-926.13750497	163.24876115	29918863.17497490	32.18	0.0013
DR02NV	-180.08589090	113.91468385	2323239.01049199	2.50	0.1650

BOUNDS ON CONDITION NUMBER: 1.023531, 4.094125

THE ABOVE MODEL IS THE BEST 2 VARIABLE MODEL FOUND.

MINIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE ENERGY

STEP 1 VARIABLE DRMAXV ENTERED R SQUARE = 0.01031646 C(P) = 11.39513138

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	1	45906.21620535	45906.21620535	0.07	0.7949
ERROR	7	4403896.67268354	629128.09609765		
TOTAL	8	4449802.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	2802.74409210				
DRMAXV	31.06085373	114.98658602	45906.21620535	0.07	0.7949

BOUNDS ON CONDITION NUMBER: 1, 1

STEP 1 DRMAXV REPLACED BY DR02NV R SQUARE = 0.17830831 C(P) = 8.61217260

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	1	793436.84639760	793436.84639760	1.52	0.2576
ERROR	7	3656366.04249129	522338.00607018		
TOTAL	8	4449802.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	5326.74559782				
DR02NV	-104.02515533	84.40302344	793436.84639760	1.52	0.2576

BOUNDS ON CONDITION NUMBER: 1, 1

STEP 1 DR02NV REPLACED BY DR02FV R SQUARE = 0.20021401 C(P) = 8.24928209

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	1	890912.87706283	890912.87706283	1.75	0.2272
ERROR	7	3558890.01182605	508412.85883229		
TOTAL	8	4449802.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	5789.56173759				
DR02FV	-136.62398734	103.20900733	890912.87706283	1.75	0.2272

BOUNDS ON CONDITION NUMBER: 1, 1

MINIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE ENERGY

STEP 1 DR02FV REPLACED BY RIBV R SQUARE = 0.55319506 C(P) = 2.40178593

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	1	2461608.97486395	2461608.97486395	8.67	0.0216
ERROR	7	1988193.91402494	284027.70200356		
TOTAL	8	4449802.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	10261.92679537				
RIBV	-288.46567007	97.98620830	2461608.97486395	8.67	0.0216

BOUNDS ON CONDITION NUMBER: 1, 1

STEP 1 RIBV REPLACED BY SPINEV R SQUARE = 0.68284100 C(P) = 0.25406681

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	1	3038507.86374262	3038507.86374262	15.07	0.0060
ERROR	7	1411295.02514626	201613.57502089		
TOTAL	8	4449802.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	11123.60182995				
SPINEV	-291.73098469	75.14710614	3038507.86374262	15.07	0.0060

BOUNDS ON CONDITION NUMBER: 1, 1

THE ABOVE MODEL IS THE BEST 1 VARIABLE MODEL FOUND.

STEP 2 VARIABLE DRMAXV ENTERED R SQUARE = 0.68610141 C(P) = 2.20005475

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	2	3053016.04400270	1526508.02200135	6.56	0.0309
ERROR	6	1396786.84488619	232797.80748103		
TOTAL	8	4449802.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	10737.22013365				
SPINEV	-290.64253465	80.86749124	3007109.82779735	12.92	0.0114
DRMAXV	17.48703836	70.04856359	14508.18026008	0.06	0.8112

BOUNDS ON CONDITION NUMBER: 1.002915, 4.011662

MINIMUM R-SQUARE IMPROVEMENT FOR DEPENDENT VARIABLE ENERGY

STEP 2 DRMAXV REPLACED BY RIBV R SQUARE = 0.69114796 C(P) = 2.11645353

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	2	3075472.17080602	1537736.08540301	6.71	0.0295
ERROR	6	1374330.71808287	229055.11968048		
TOTAL	8	4449802.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	11352.15125685				
RIBV	-65.20075560	162.30479322	36964.30706340	0.16	0.7018
SPINEV	-241.86048269	147.74034840	613863.19594207	2.68	0.1527

BOUNDS ON CONDITION NUMBER: 3.40215, 13.6086

STEP 2 RIBV REPLACED BY DR02FV R SQUARE = 0.69531653 C(P) = 2.04739678

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	2	3094021.50573262	1547010.75286631	6.85	0.0283
ERROR	6	1355781.38315627	225963.56385938		
TOTAL	8	4449802.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	11290.95665187				
SPINEV	-273.54818330	87.60624926	2203108.62866978	9.75	0.0205
DR02FV	-37.55542677	75.76908616	55513.64198999	0.25	0.6378

BOUNDS ON CONDITION NUMBER: 1.212626, 4.850505

STEP 2 DR02FV REPLACED BY DR02NV R SQUARE = 0.77310821 C(P) = 0.75869717

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	2	3440179.14293033	1720089.57146516	10.22	0.0117
ERROR	6	1009623.74595856	168270.62432643		
TOTAL	8	4449802.88888889			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	12054.45053838				
SPINEV	-275.46013553	69.45557020	2646742.29653273	15.73	0.0074
DR02NV	-74.88039603	48.46596853	401671.27918770	2.39	0.1733

BOUNDS ON CONDITION NUMBER: 1.023531, 4.094125

THE ABOVE MODEL IS THE BEST 2 VARIABLE MODEL FOUND.

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